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SINGLE-CYLINDER DIESEL ENGINE TESTS
WITH UNSTABILIZED WATER-IN-FUEL EMULSIONS

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16. Abstract

A single-cylinder, four-stroke cycle diesel engine was operated on unstabilized water-in-fuel emulsions. Two prototype devices were used to produce the emulsions on-line with the engine. More than 350 test points were run with baseline diesel fuel and emulsified water-in-fuel. Water content of the emulsified fuel varied from about 2% to 23% by volume. Statistically significant decreases in fuel consumption, ranging from 1.2% to 5.1% were obtained with emulsified fuels in 20 out of 36 test conditions. An increase of 2.5% was measured at one condition only. Use of the emulsified fuels decreased oxides of nitrogen by up to about 60% and Bosch smoke numbers by up to almost 70%, whereas unburned hydrocarbons increased up to over 130%. Carbon monoxide changes with emulsified fuel varied from a decrease of 52% to an increase of over 170%, depending on engine speed and power, and water content of the fuel. No problems were encountered in engine operation at any test condition with the water-in-fuel emulsions.

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PREFACE

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1. INTRODUCTION

1.1   Background

The current emphasis on energy conservation has precipitated the investigation of a number of devices and techniques oriented toward fuel savings. There is presently a high level of interest, particularly among large users of liquid fuels, in system modifications or fuel additives that can diminish fuel requirements or extend available fuel supplies.

Among the suggestions that have been made in the interest of fuel conservation is the recommendation that water be added to liquid engine fuels as a means of enhancing combustion properties and extending supplies. Water addition has received dramatic coverage in the popular press, although some reports have been without basis in technical fact. A number of systems and devices have been announced, and enthusiastic claims have been made for their efficacy.

Performance claims which are obviously excessive or thermodynamically unsound can generally be recognized and disregarded; however, there are also reports and data from reliable investigators that indicate some advantage as a result of the addition of water to fuel. Most notably, the use of water-in-fuel emulsions (i.e., the fuel forms the continuous phase, the water the discontinuous phase) has been associated with significant reductions in the emission of smoke and/or oxides of nitrogen from continuous burners, such as those used in turbine engines[1]*, furnaces and boilers[2]. The available results also indicate that similar advantages may be obtained through use of fuel-water emulsions in internal combustion engines[3,4].

The basic mechanism which is postulated for combustion of fuel-water emulsions is the presence of "micro-explosions". It is believed that a droplet of emulsion occurring in the spray from a fuel nozzle contains a number of discrete globules of water surrounded by fuel. When the droplet is heated, the water remains in the liquid state until a temperature far above the boiling point is attained. The transition to the vapor phase occurs quite rapidly and violently, and the fuel droplet is divided or shattered into smaller entities (so-called secondary atomization). The result of this process in an engine cylinder would be improved mixing of fuel and air, with resulting improved combustion. The micro-explosion phenomenon has been demonstrated in laboratory experiments[5], and basic theoretical research efforts[6] are presently underway that will define the nature of the emulsions that will yield maximum mixing effects under engine operating conditions.

In the absence of this basic data, the studies on various combustion systems must be considered. These experiments are in some degree lacking, since all of the pertinent variables have not been defined, and all of the

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*Numbers in parentheses designate References at end of report.

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determine the advisability of pursuing both the testing program with large-scale engines and a development program for enhanced fuel-water emulsification capability.

It should be noted that comparison of these particular emulsification devices was specifically not an objective of this program. Both of the systems supplied to the Institute were thoroughly protected by non-disclosure agreements, and neither Institute nor Government personnel were allowed to examine the internal components of the emulsifiers. Instead, the testing program was oriented toward evaluation of the possible benefits that might result from the use of the products supplied by the two emulsification systems. Specific comparisons between systems should be made only after systems are available for complete examination and after test data are obtained from the engines that the devices will serve in the field.

1.3   Approach

The approach utilized by Institute investigators in this study can best be characterized as direct rather than basic. No attempt was made to optimize emulsion characteristics or to investigate specific relationships between fuel-water emulsions and the combustion process. Instead, a single-cylinder engine was operated using both conventional diesel fuel and emulsions generated by the two emulsification systems supplied by the Coast Guard. In all cases, the emulsions were of the unstabilized type; no surfactants were added to prolong the lifetime of the fuel-water mixture. Both of the emulsification systems were attended by the developers or their representatives during most of the tests.

In order to determine whether a potential advantage existed for the use of emulsions in Coast Guard vessels, tests were conducted using a single-cylinder research engine equipped with comprehensive instrumentation, and detailed measurements of fuel consumption and engine operating parameters were made. The sequence of test runs was constructed in such a way that individual tests with emulsions were immediately preceded by tests with conventional diesel fuel at the same engine condition. Using this technique, baseline data were acquired concurrent with the data on the test fuel, and reliance on previously executed baseline information was unnecessary. The tests at each test condition were repeated from four to six times, and statistical tests were applied to the fuel consumption data in order to define the confidence level associated with any observed changes in the numerical values.

During the period of performance of the engine tests, the quality of the fuel-water emulsion generated by each system was monitored by representatives of the Transportation Systems Center and the United States Coast Guard. Samples were drawn of the emulsion that was supplied to the engine, and data were obtained by photographing the emulsion through an optical microscope, by allowing the samples to settle in a graduate, and by centrifuging a sample to

2. EXPERIMENTAL APPARATUS AND TECHNIQUES

The study of fuel-water emulsions was performed using a single-cylinder laboratory test engine as the primary analytical tool. Although wide use of emulsions in single-cylinder engines is not likely, the laboratory engine does offer the opportunity for excellent control of an experiment, and it allows the application of a broad range of instruments for the determination of fuel-dependent parameters. Furthermore, definitive tests can be conducted with small quantities of fuel that would be completely inappropriate for large-scale engine tests. Single-cylinder engine experiments are widely used throughout the research and development community as a means of assessing the significance of changes in fuels, lubricants, and engine hardware.

2.1 Equipment

The test engine used in this program was manufactured by the Laboratory Equipment Company (Figure 2.1). The bore and stroke are 3.8125 and 3.750 inches, respectively; the displacement is 42.8 cubic inches. The engine was equipped with a standard open-chamber diesel head and a "Mexican hat" piston. The compression ratio was 16.7:1. A 60 degree shroud was installed on the intake valve in order to produce the proper air swirl rate within the combustion chamber. The basic engine fuel system included a Bosch APE1B injection pump with an 8 mm barrel and plunger and a TMB variable timing assembly. Injection of fuel into the cylinder was accomplished with a Sims NL141 (4-hole) nozzle set to a valve opening pressure of 2150 psi. The intake valve was open from 18 degrees before top dead center to 58 degrees after bottom dead center, and the exhaust valve was open from 124 degrees after top dead center to 20 degrees after top dead center. Maximum lift for both valves was 0.228 inch. The engine assembly included a massive flywheel and a system of rotating counterweights to provide smooth operation over the speed range.

The engine was connected to a cradled dry-gap, eddy-current dynamometer capable of absorbing 30 hp. The engine-dynamometer assembly was connected through a clutch to a 20 hp electric motor which was utilized for engine starting and measurement of motored engine friction at any speed up to 2500 rpm (Figure 2.2).

Engine speed was determined through the use of a magnetic pickup and a 60-tooth gear installed in the engine-dynamometer coupling. The speed signal was transmitted to a digital counter used as an output device. In addition, the signal from the magnetic pickup was supplied to a Digalog dynamometer controller capable of maintaining engine speed to plus or minus one rpm. Engine load was varied through adjustment of the fuel delivery rate, and measurement of the load was effected by observation of the force transmitted between the cradled dynamometer and a BLH load cell. The bridge circuitry for the load cell allowed determination of the beam load to within 0.1 lb.
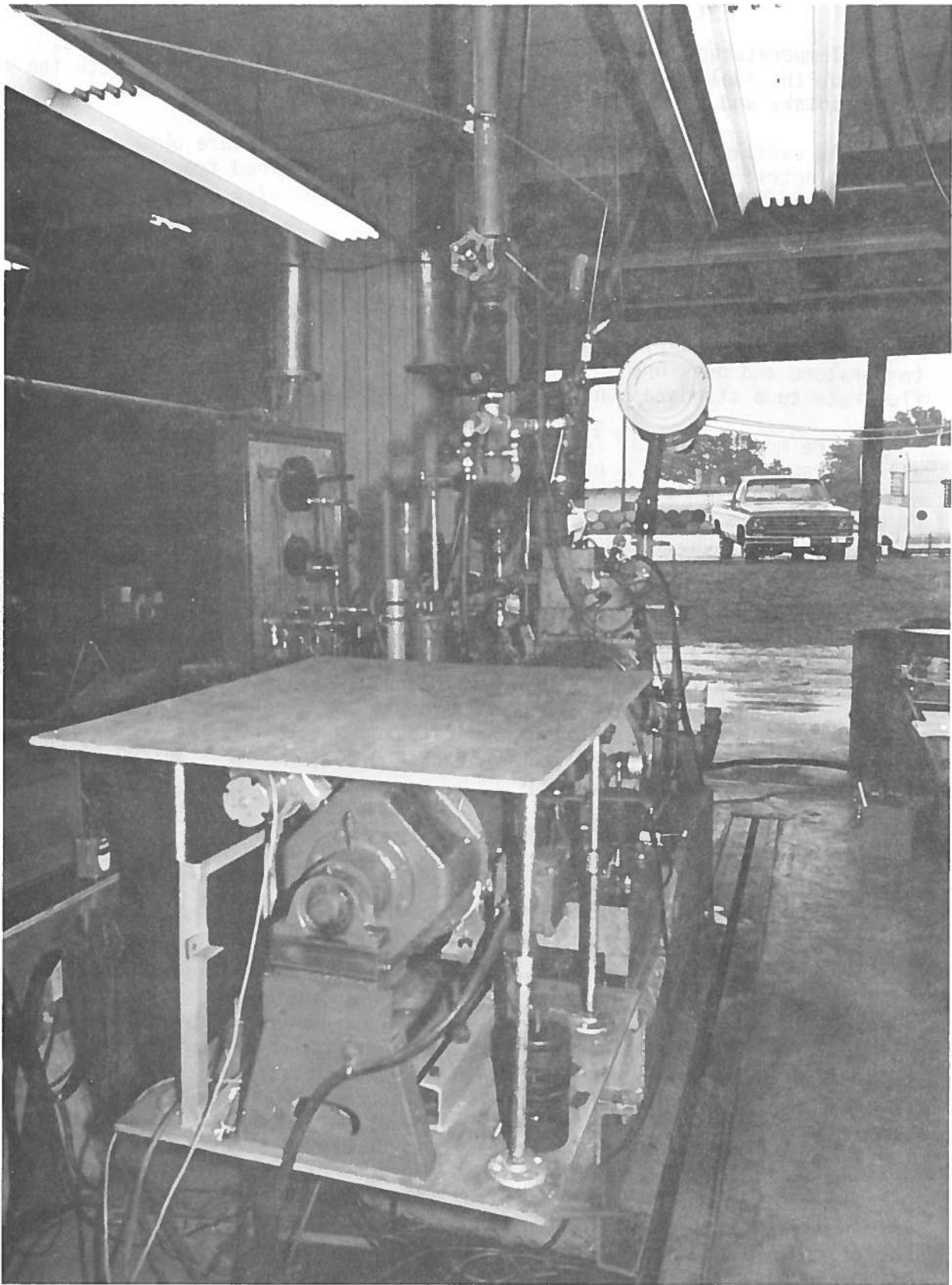
FIGURE 2.2 - REAR VIEW OF TEST ENGINE AND MOTORING DYNAMOMETER

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Diesel or Water/Fuel Emulsion

Graduated Burette

Water/Fuel Emulsion

Weigh Scale

Diesel Fuel

Injection Pump

Transfer Pump

Fuel Injector
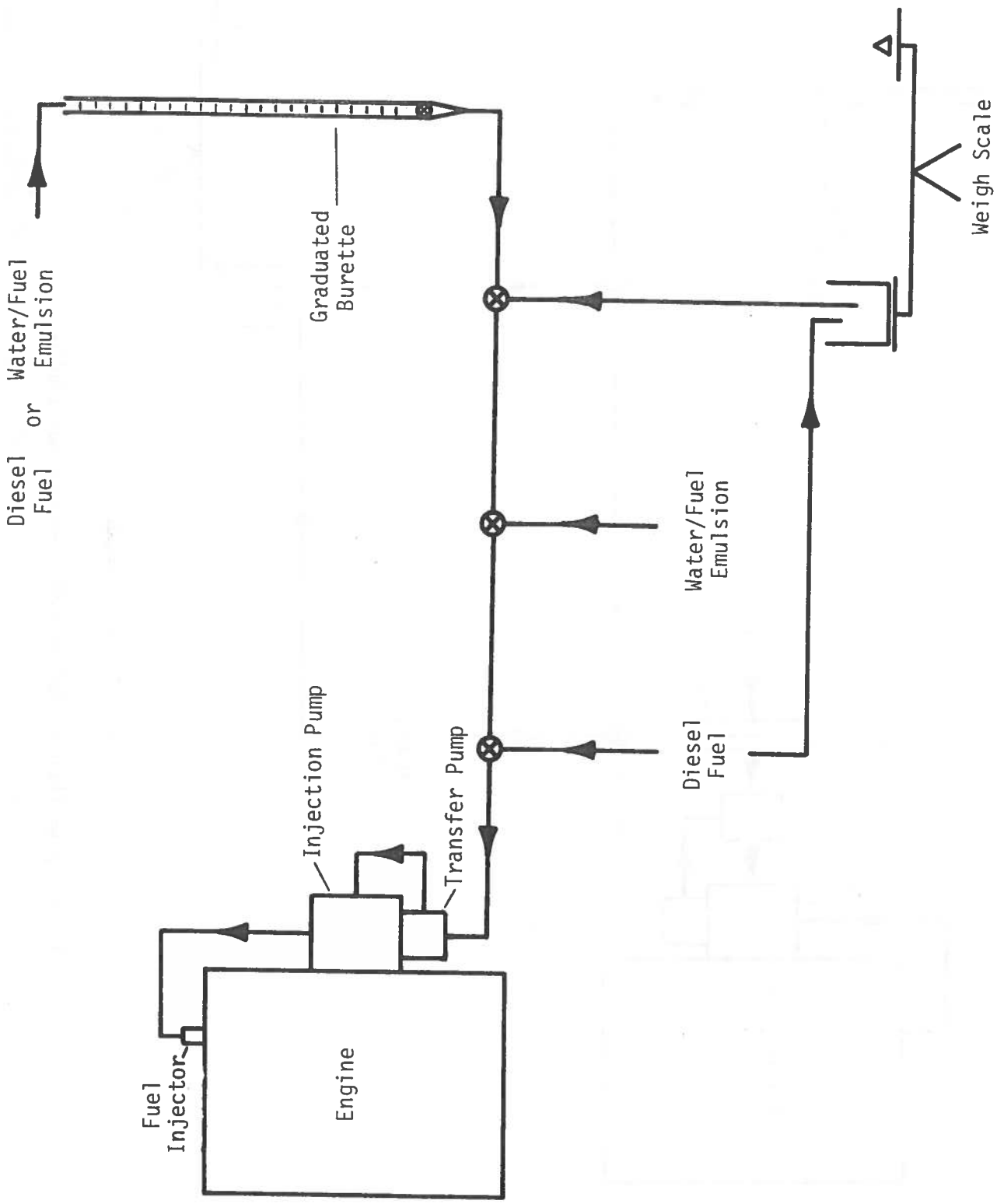
Engine

FIGURE 2.3- FUEL SYSTEM SCHEMATIC--DAEDALEAN EMULSIFIER
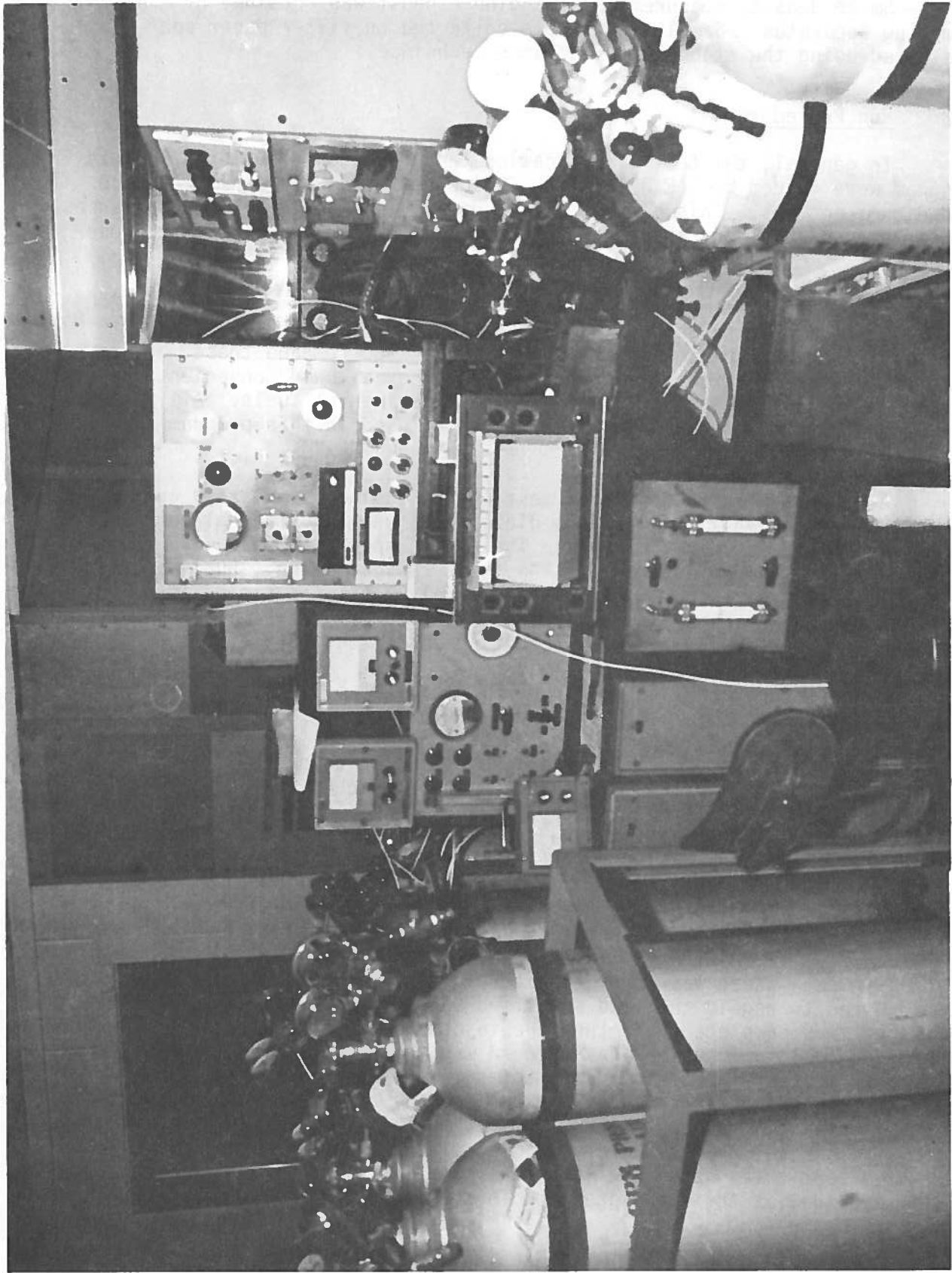
FIGURE 2.5 - GASEOUS EMISSIONS INSTRUMENTATION

TABLE 2.1 - ENGINE TEST CONDITIONS

Engine rpm	Nominal IMEP, psi	Nominal Vol. % Water-In-Fuel
Daedalean Emulsions		
1000	60	10, 20
	75	10, 20
	90	10, 20
2000	68	10, 15, 20
	82	10, 15, 20
	96	10, 15, 20
2500	70	20
	85	20
	100	20
Dynatrol Emulsions		
1000	60	6.4, 14.5, 23.5
	75	5.2, 12.0, 20.2
	90	4.3, 10.0, 17.0
2000	68	3.3, 7.8, 13.5
	82	2.6, 6.3, 11.2
	96	2.1, 5.0, 8.9

The data acquisition form provided to the engine operator specified the test conditions at each point by designating the desired speed, load, injection timing, and fuel (diesel fuel or emulsion water content). In addition, values for the coolant outlet temperature and the oil sump temperature were specified. A sample of the data sheet is included as Figure 2.6.

The desired test conditions were set and maintained by the engine operator, and the observed values of all parameters were recorded after a stable operating condition had been achieved. For the tests with the DAI emulsifier, water content of the fuel was obtained on a daily basis by averaging the water content of centrifuged samples obtained at hourly intervals through-out the testing process. The Dynatrol emulsifier did not require the production of fuel in excess of the engine requirements, and water content was measured directly by calibrated flowmeters.

The engine air flow was obtained from the calibration curve of the laminar flow element. The flow rate indicated by the observed pressure drop across the metering element was corrected for the filter pressure drop, the ambient (barometric) pressure, and the ambient temperature in order to obtain the value in standard cubic feet per minute. This result was then converted to pounds per hour.

The observed engine speed and dynamometer beam load were used, along with the dynamometer constant, to obtain brake horsepower (BHP). Similar data, obtained while the engine was being motored, were used to calculate friction horsepower (FHP). The brake horsepower was corrected for ambient conditions using the correction factor described in SAE J816b for diesel engines, and the corrected brake and friction horsepower values were added to yield the indicated horsepower (IHP).

The values for engine displacement, speed, and horsepower were utilized for the calculation of the brake, friction, and indicated mean effective pressures. The mean effective pressure is proportional to torque and is useful as a plotting parameter for the comparison of other quantities.

The flow rates of diesel fuel were obtained in terms of the time required for consumption of a known mass of fuel; the measured values were converted to units of pounds per hour. The flow rates for both diesel fuel and fuel-water emulsion were also measured by means of a volumetric technique; the time required for consumption of a measured volume of fuel was recorded. In this case the density of the fuel, at the temperature of the metered flow, was obtained from the API gravity (Appendix A) and used in the conversion from volume to mass. When emulsions were measured with the volumetric meter, a density was calculated from the actual measured water content (obtained by centrifuging samples of emulsion and measuring the volume of water in the bottom of the centrifuge tubes), the fuel density, and the water density. Both densities were obtained at the temperature of the fluid in the metering system. For emulsions, flow rates were calculated for both the total liquid flow and the diesel fuel flow into the engine; the latter quantity was used in subsequent calculations of specific fuel consumption.

The ratio of the fuel flow and the engine horsepower output yields the specific fuel consumption; this value was calculated for both the brake and indicated power. Another useful ratio, the engine thermal efficiency, was obtained from the indicated horsepower output, the fuel rate, and the lower heating value of the fuel. In addition, the ratio of the fuel mass flow rate and the air mass flow rate yields the fuel-air ratio, a typical indicator of engine loading.

Since the data acquisition process at each engine test point and each fuel blend was repeated from four to six times, it was possible to calculate the mean and standard deviation for each set of similar runs. The Student's t-distribution was then utilized to obtain the interval that would contain the mean with a 90% confidence. With this information available for each set of data, it was possible to specify whether or not a difference existed between the mean of the runs with diesel fuel and the mean of the runs with fuel-water emulsion at each test condition.

In general, no calculations were performed on the gaseous emissions data. The numerical values (in parts per million or percent) obtained from the sampling instruments were used for comparing the effects of emulsified and baseline fuels. An exception to this procedure was the calculation of a carbon balance between the carbon in the fuel and the carbon in the exhaust, as determined by the concentration data for unburned hydrocarbons, CO, and, most importantly, CO_2.

3. DISCUSSION OF TEST RESULTS

In this section, we discuss the effect of emulsified fuels on the most pertinent engine data obtained in this test series. Some tables and graphs of data are presented in the text for easy reference, while supplementary tables and graphs are included in Appendix B. This section also contains qualitive discussions of the effect of these emulsified fuels on general engine operation. The data obtained with the two emulsification devices are compared only to try to show consistency in results when emulsified fuel is used. It is not intended that there should be a competition between the emulsifiers; indeed, such an approach would be inappropriate since little can be said about the type or qulaity of water-in-fuel emulsions produced by the two devices.

3.1   Indicated Specific Fuel Consumption

Statistically significant (90% confidence level or greater) improvements in indicated specific fuel consumption (ISFC) were obtained through use of emulsified fuel for twenty of thirty-six engine test conditions (10 of 18 for each emulsification device). The average improvement at these 20 test points was 3.0%. At 1000 and 2000 rpm, the common test speeds for both emulsifiers, the average reduction in ISFC was 1.9% and 3.1%, respectively. At 2500 rpm (Daedalean emulsifier only) the average established reduction was 5.1%. Average fuel consumption values (along with other engine performance and emissions data) for each test condition are shown in Appendix Tables B-1 and B-2 for Daedalean and Dynatrol emulsions, respectively these ISFC values are graphed as functions of indicated mean effective pressure (IMEP) in Figures B-1 through B-6 (Daedalean) and Figures B-7 through B-12 (Dynatrol) of this same appendix.

Figures 3.1 through 3.3 show the percentage change in ISFC as a function of emulsified fuel-water content for each engine speed/load test condition used in conjunction with the Daedalean emulsifier. At 1000 rpm (Figure 3.1) one statistically established reduction (2.7%) was obtained at the highest IMEP (90 psi) with the highest water content used (20%). Better results were obtained at 2000 rpm (Figure 3.2), where seven of nine test points showed ISFC improvements ranging from 2.4 to 4.8% (average of 3.7%). These reductions occurred at all three engine loads for 15 and 20% water content. The optimum water content appears to be 15%, since the largest reductions in ISFC occur at this point. At 2500 rpm (Figure 3.3), where only 20% water content was tested, a 5.1% reduction was obtained at the two higher load points. The lightest engine load (70 psi IMEP) barely missed showing a reduction (2.5%) at the 90% confidence level. The reduction actually passes at about 85% confidence, however.

Summarizing the results obtained with the Daedalean emulsions: of the 10 test conditions at which a statistically established reduction in ISFC was found, the average improvement was 3.9%. Considering only the reductions that occurred at the two lower engine speeds, the average improvement was 3.6%.

The corresponding data obtained with emulsions produced by the Dynatrol device are shown in Figures 3.4 (1000 rpm) and 3.5 (2000 rpm).

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FIGURE 3.2- EFFECT OF EMULSIFIED FUEL WATER CONTENT ON ENGINE SPECIFIC
FUEL CONSUMPTION AT 2000 REV/MIN--DAEDALEAN EMULSIFIER

Engine Speed: 1000 rpm

IMEP, psi
● 60
■ 75
▲ 90

Percent Change in ISFC

+5 +4 +3 +2 +1 0 -1 -2 -3 -4 -5

Water In Fuel, Vol. %

0   5   10   15   20   25

*Denotes Established Change
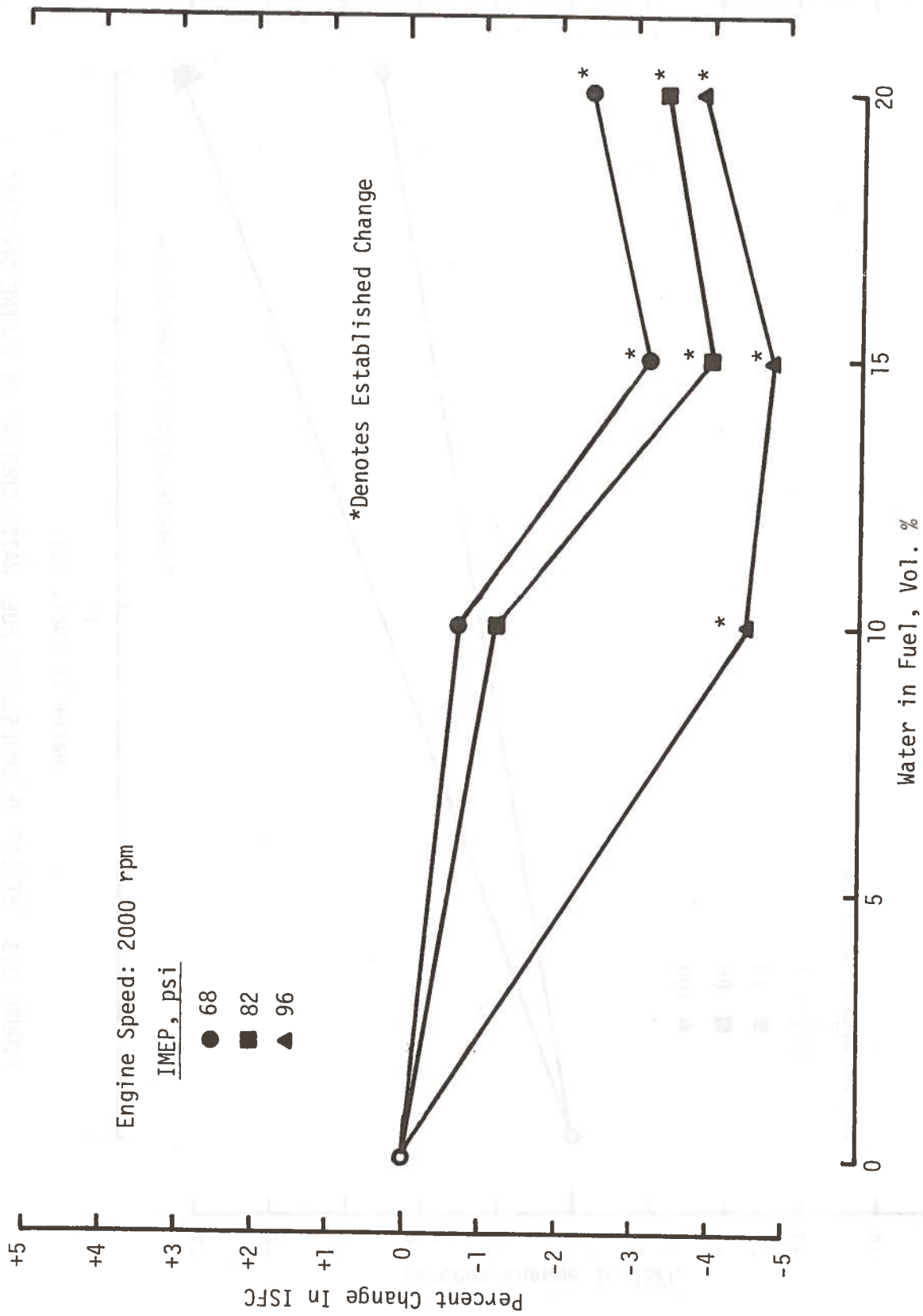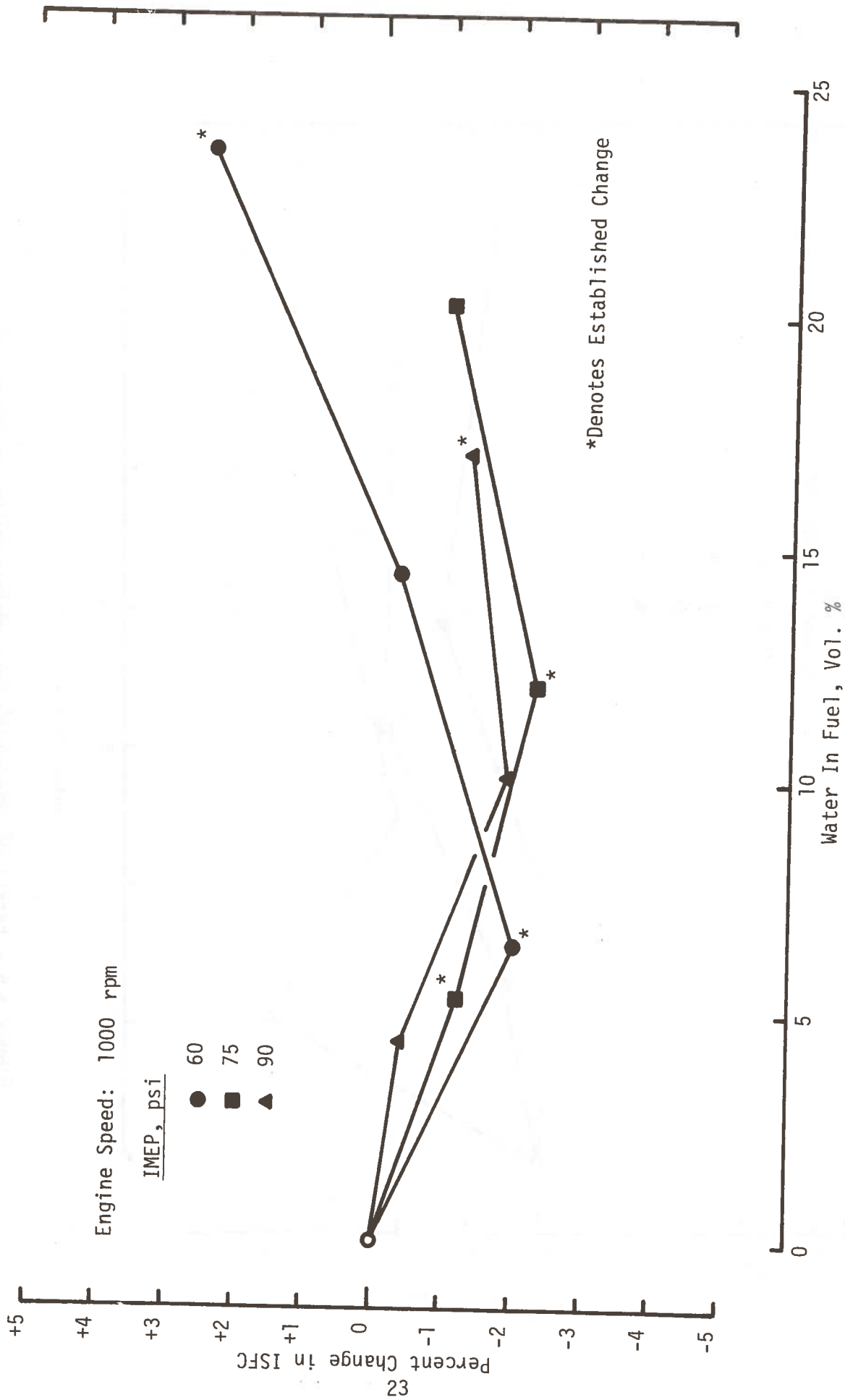
FIGURE 3.4 – EFFECT OF EMULSIFIED FUEL WATER CONTENT ON ENGINE SPECIFIC FUEL CONSUMPTION AT 1000 REV/MIN--DYNATROL EMULSIFIER

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For tests at the lower speed, the fuel-water content varied from about 4 to 23.5% by volume, a greater range than was employed in tests with the Daedalean emulsions. It appears that the lighter loads benefited from low (5 to 6%) water content, while the maximum load point required somewhat more water input in order to effect a reduction in ISFC. The lowest IMEP condition suffered a degradation in fuel consumption at the maximum water content. In all, five of the nine test points had statistically established changes in ISFC: four decreases ranging from 1.2 to 2.3% (average of 1.7%) and one increase of 2.5% at the light load-high water content condition. These data definitely show that water content can and should be optimized to the engine operating condition.

At 2000 rpm (Figure 3.5), fuel-water content ranged from about 2 to 13.5%. Established reductions in ISFC were found at six of nine test conditions; these reductions ranged from 1.4 to 3.9%, with an average of 2.4%. Improvement occurred for all three water contents at maximum IMEP, for two points at the medium IMEP, and for only one point at the lowest IMEP. Note that some of the reductions occurred with quite low water content. These data complement those obtained at this engine speed with Daedalean emulsions (Figure 3.2) in that the ISFC for the higher load is again shown to be more susceptible to improvement than is fuel consumption at lower IMEP. Or, alternately, it appears that optimization of the fuel-water content to obtain a reduction in fuel consumption is less critical at higher load than at lighter loads.

To summarize, it was found that use of emulsified fuel from the Dynatrol device resulted in improved ISFC at 10 test points, with an average reduction of 2.1%. There was one instance of an increase in fuel consumption that was probably due to use of too great a water content at the particular engine condition.

3.2   Exhaust Smoke Density

Although Bosch smoke numbers were obtained for all test points, it is our opinion that only Bosch numbers at least equal to 1.0 should be analyzed, since this smoke level corresponds to a PHS smoke meter opacity of less than 2%, which is below the limit of visibility. Not only is smoke density below this level not significant, but such data tends to have a large amount of variation or scatter. Repeatability is much better at Bosch numbers of 1.0 or above. However, all smoke data is presented in summary Tables B-1 and B-2 of the appendix.

The smoke data obtained with Daedalean emulsions are shown in Figure 3.6. It can be seen that consistent reductions in smoke density were obtained. At 1000 and 2000 rpm, where more than one water content was used, the decrease was approximately linear with water content. In general, baseline smoke numbers were reduced by one-third to two-thirds, depending on fuel-water content. The average reduction for the seven test points shown in the figure was approximately one-half(45%).

Smoke data obtained with the Dynatrol emulsions are shown in Figure 3.7. The smoke reduction trend is not as consistent here as for the previous data. It appears that the maximum fuel-air ratio condition (96 psi IMEP) at 2000 rpm might have benefited from more water in the fuel, while smoke density at the other conditions is not sustantially influenced by the emulsified fuel. However, in no case was an increase in smoke found to occur. The reductions range from approximately 10 to 36%, and the average reduction was approximately 17%.

Therefore, significant (visible) smoke density with emulsified fuel from both devices was reduced at every condition but one (where no change was observed).

3.3   Oxides of Nitrogen

Oxides of nitrogen (NO_x) concentrations obtained in tests with the Daedalean emulsifier are presented in Appendix Table B-1, while the percentage change in concentration as a function of fuel water content is shown in Figures 3.8 through 3.10. It can be seen that NO_x was reduced by the use of emulsified fuel at all speed-load points except one. In general, the highest IMEP condition required more water content than did the other two load points at each speed in order to achieve a similar percentage reduction in NO_x. In other words, a given water content resulted in a smaller reduction at maximum load than it did at lower IMEP values. This is a reasonable result since peak flame temperature and fuel-air ratio during combustion (two primary factors in NO_x formation) are highest at maximum load. In any case, the reductions in NO_x were significant and ranged from 9 to 41% (average 29%) at 1000 rpm, from 14 to 58% (average 40%) at 2000 rpm, and from 28 to 44% (average 38%) at 2500 rpm. The lone increase in NO_x was less than 10%. The average reduction for all operating conditions was approximately 35%.

The corresponding data for the Dynatrol emulsions are contained in Table B-2 and shown in Figures 3.11 and 3.12. NO_x concentration was lowered at 14 of 18 test conditions. Two increases (3 and 26%) occurred at the highest IMEP at 2000 rpm, where water content was low (2 to 9% by volume). This behavior is consistent with that observed during the Daedalean tests; i.e., it appears that maximum load conditions require more water to produce a significant reduction in NO_x. In fact, the one condition in the Daedalean test series at which increased NO_x was noted was at maximum load at 2000 rpm with 10% water content, the lowest value used.

Reductions obtained with the Dynatrol device at 1000 engine rpm ranged from 10 to 59%, (average of 30%); at 2000 rpm, the range was 14 to 39%, (average of 26%). The average reduction at these test points was 28%. The decrease in NO_x was a function of increasing fuel-water content at 1000 rpm, but at 2000 rpm this trend was not as well defined.

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FIGURE 3.8 – EFFECT OF EMULSIFIED FUEL WATER CONTENT ON OXIDES OF NITROGEN CONCENTRATION AT 1000 REV/MIN--DAEDALEAN EMULSIFIER

FIGURE 3.10 – EFFECT OF 20% WATER-IN-FUEL EMULSION ON OXIDES OF NITROGEN CONCENTRATION AT 2500 REV/MIN--DAEDALEAN EMULSIFIER
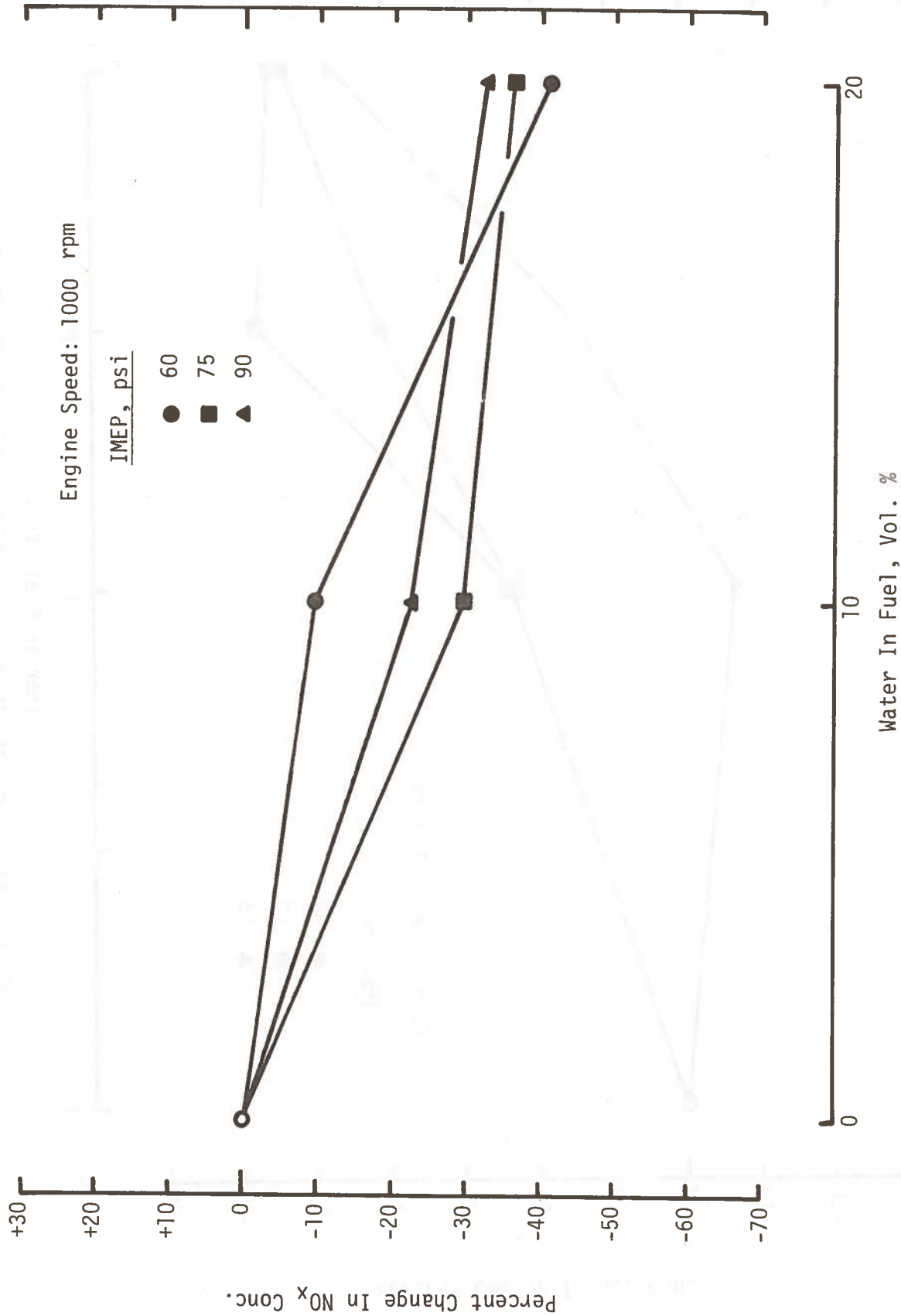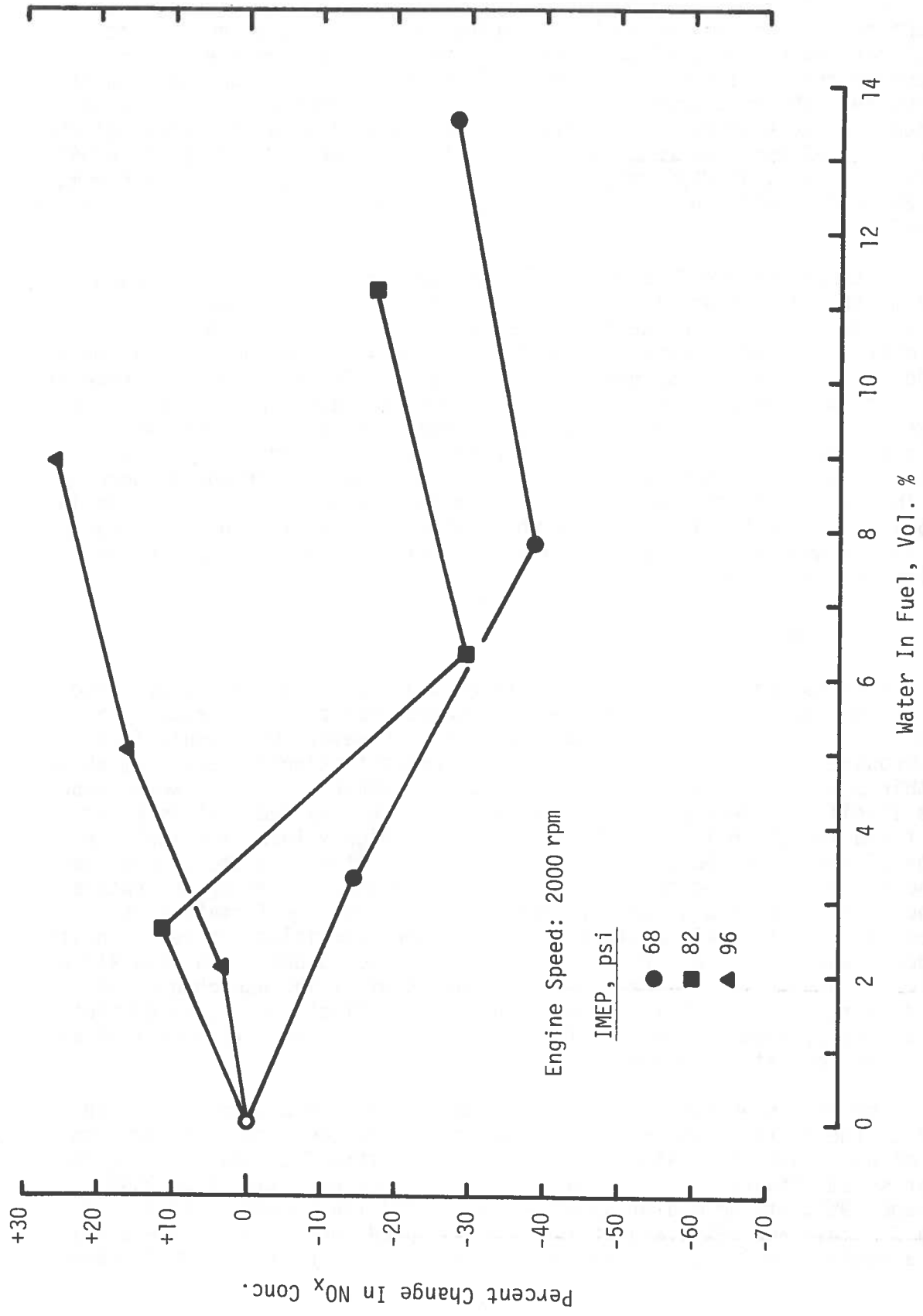
FIGURE 3.12 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON OXIDES OF
NITROGEN CONCENTRATION AT 2000 REV/MIN--DYNATROL EMULSIFIER

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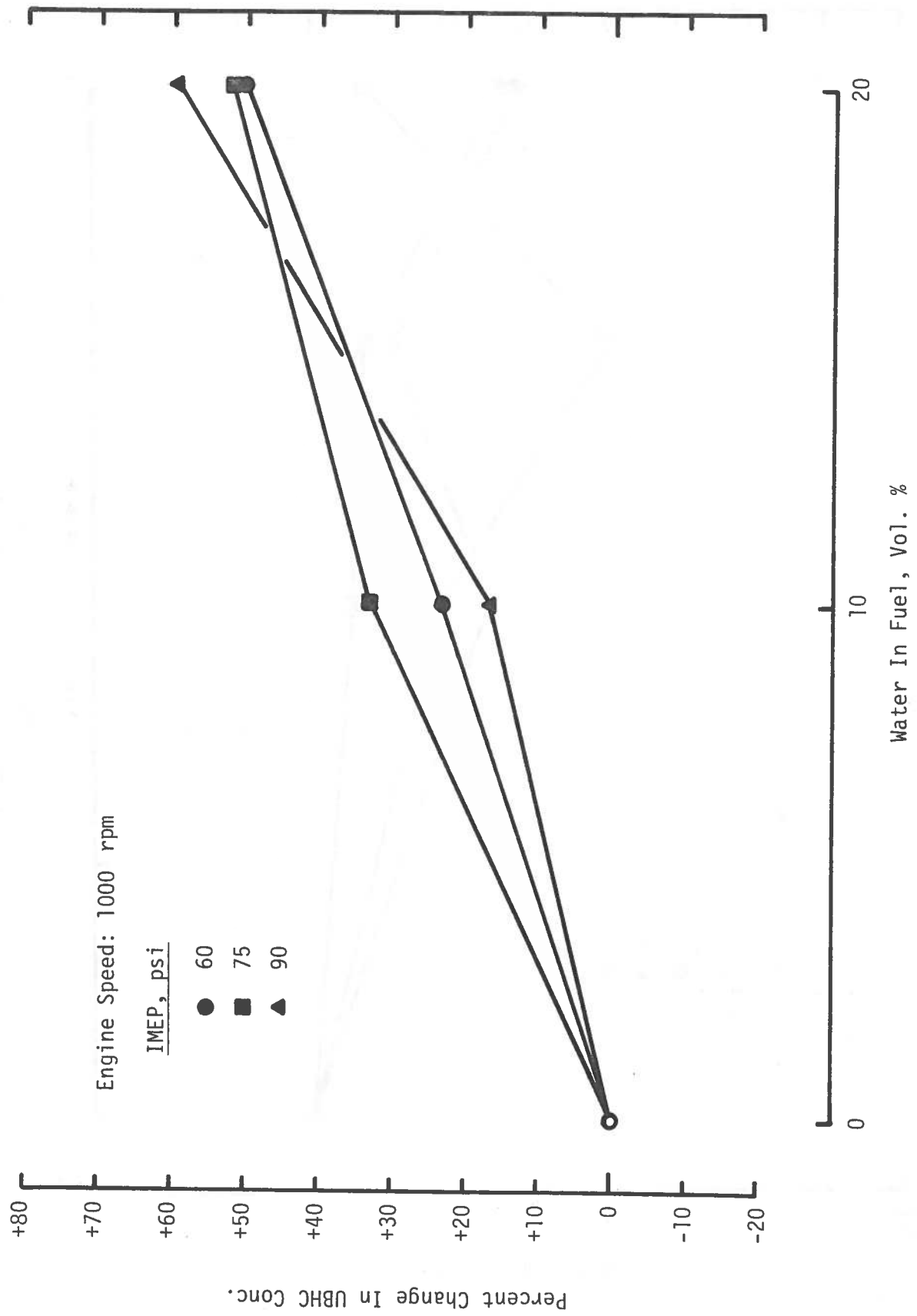
FIGURE 3.13 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON UNBURNED HYDROCARBONS CONCENTRATION AT 1000 REV/MIN--DAEDALEAN EMULSIFIER

Engine Speed: 2500 rpm

IMEP, psi
● 70
■ 86
▲ 100

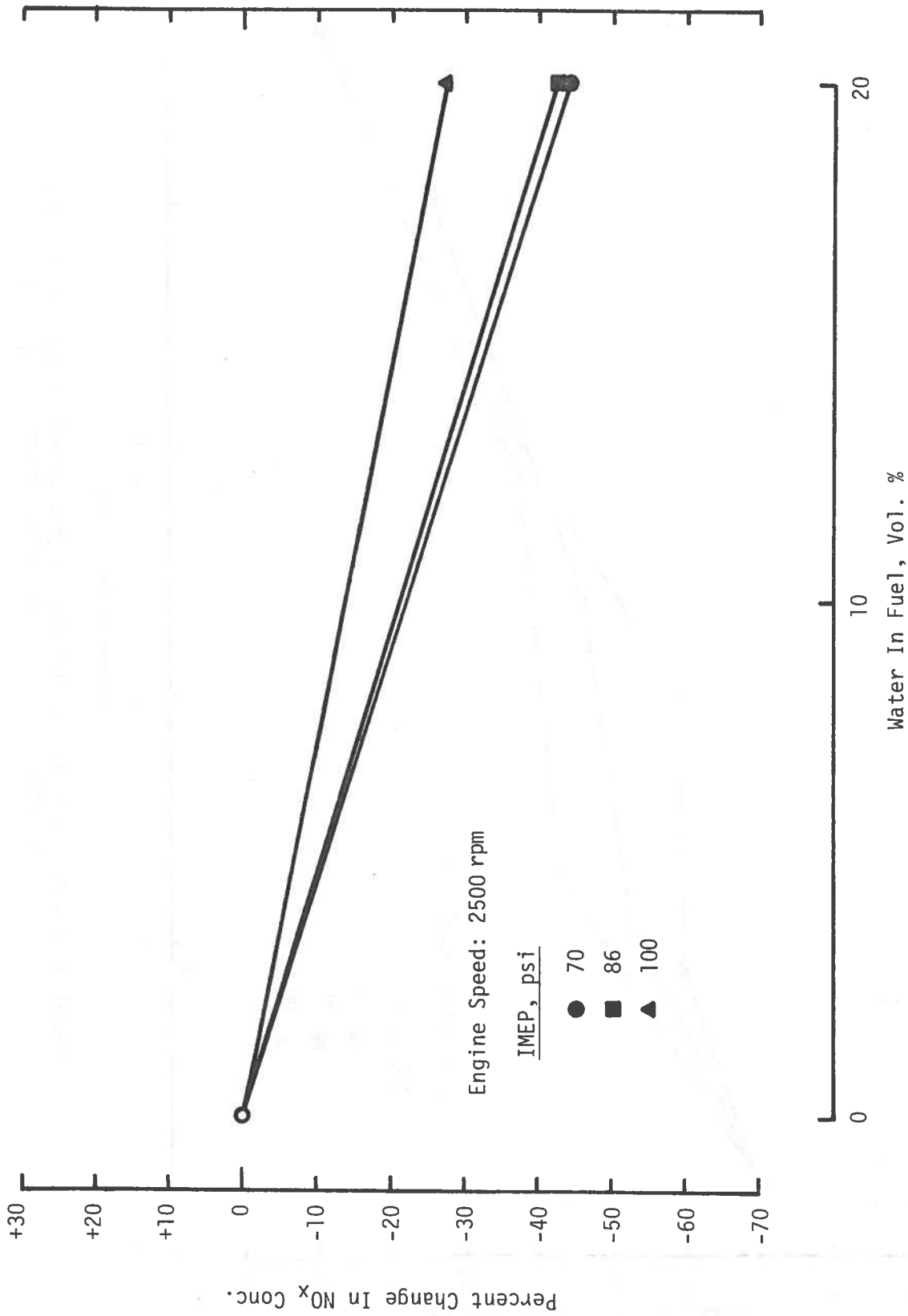Percent Change In UBHC Conc.
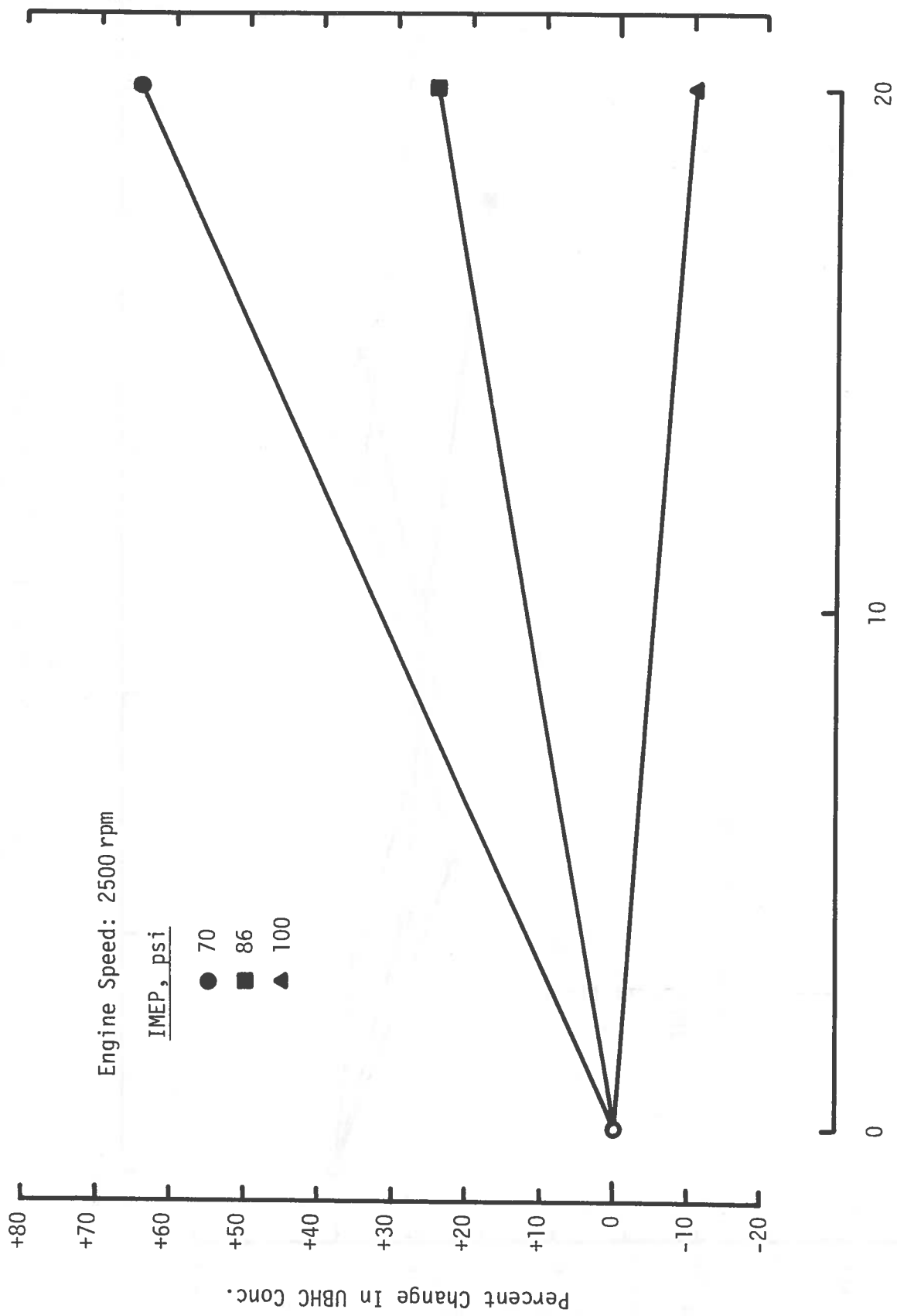
Water In Fuel, Vol. %

FIGURE 3.15.- EFFECT OF 20% WATER-IN-FUEL EMULSION ON UNBURNED
HYDROCARBONS CONCENTRATION AT 2500 REV/MIN--DAEDALEAN EMUSLIFIER
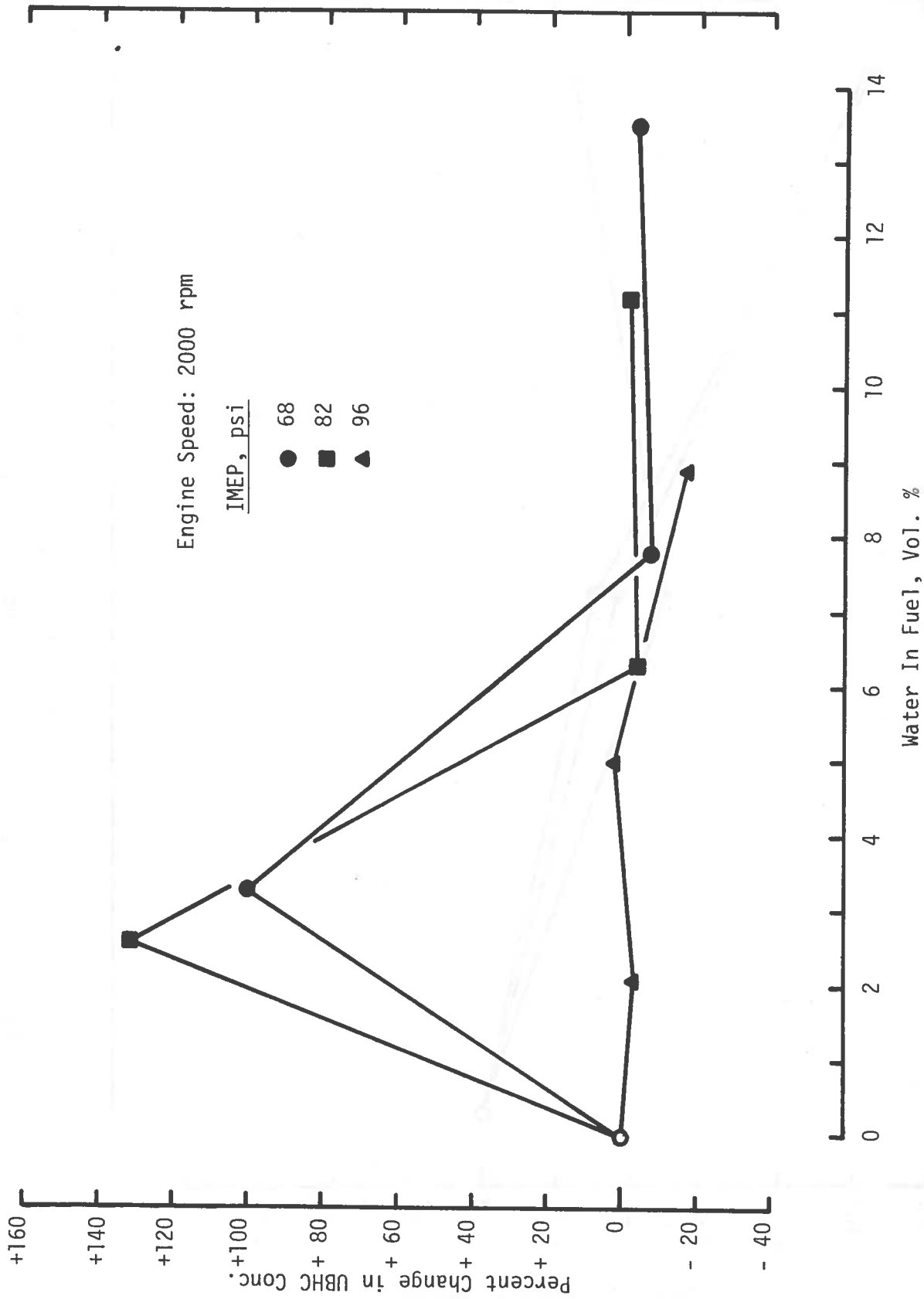
FIGURE 3.17 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON UNBURNED
HYDROCARBONS CONCENTRATION AT 2000 REV/MIN--DYNATROL EMULSIFIER

Engine Speed: 2000 rpm

IMEP, psi

● 68
■ 82
▲ 96

Water In Fuel, Vol. %

Percent Change In CO Conc.

+120 +100 + 80 + 60 + 40 + 20 0 - 20 - 40 - 60 - 80

0 5 10 15 20

FIGURE 3.19 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON CARBON MONOXIDE
CONCENTRATION AT 2000 REV/MIN--DAEDALEAN EMULSIFIER

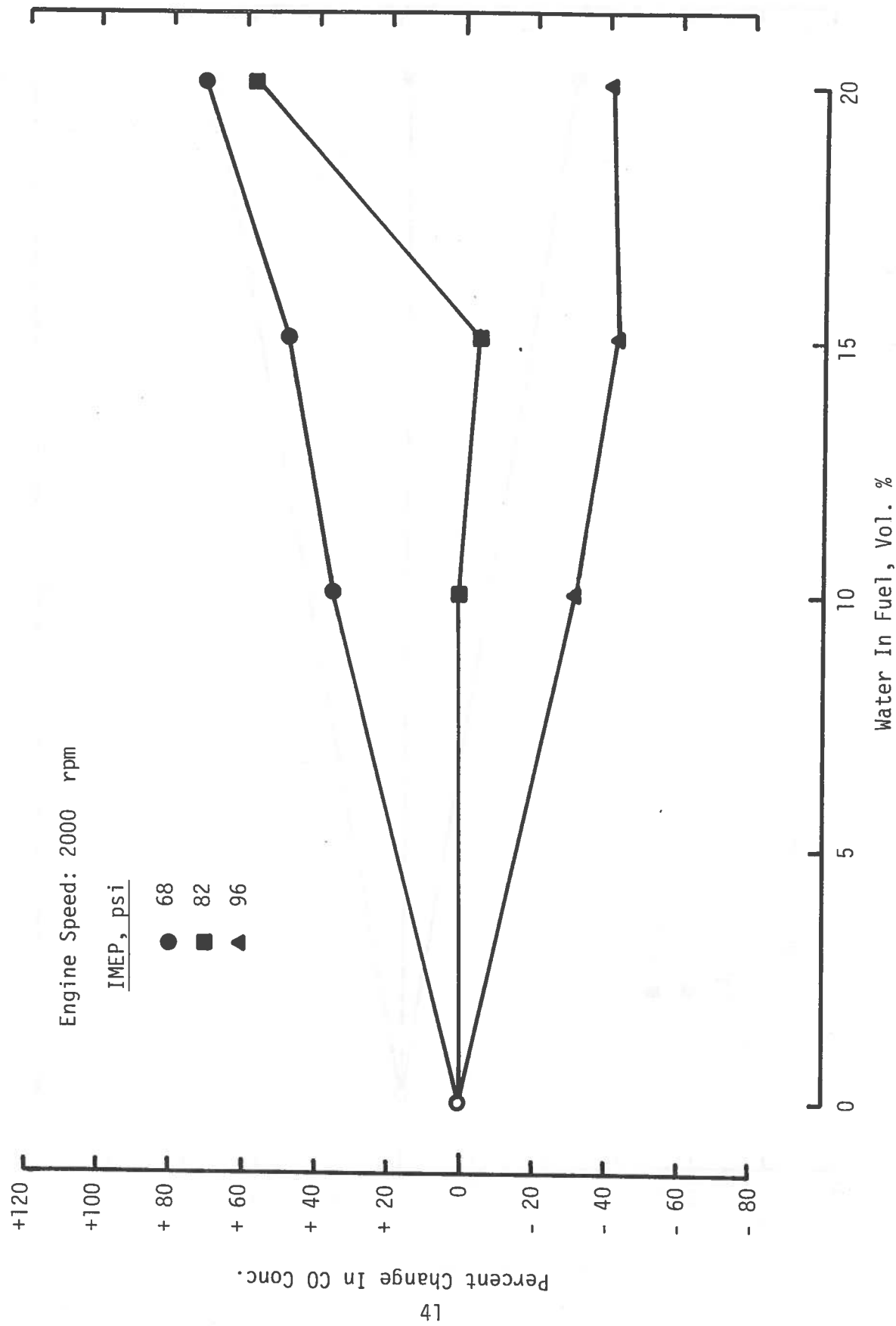at all three engine speeds was 51%, and for the two lower speeds only, 56%. There were five instances (mostly at the higher speed/load conditions) where CO concentration decreased; these changes ranged from 6 to 52%, with an average of 35%.

Similar changes in CO were found with the Dynatrol emulsions. Increases in concentration occurred at eleven test points, while decreases were found at six conditions (concentration at one condition was unchanged). At 1000 rpm (Figure 3.21), increased concentration went from 8 to 172% (average of 56%), and 2000 rpm (Figure 3.22) the range was from 11 to 90% (average of 46%). The overall average increased at both speeds was 53%. Decreased concentration was again observed principally at higher loads at 2000 rpm. These decreases were from 21 to 37%, with an average of 32%.

3.6 Carbon Dioxide Measurement and Carbon Balance Calculations

Carbon Dioxide (CO_2) was measured in order that a carbon balance calculation could be made. The usual purpose of this calculation is to determine the intake air mass flow rate for an engine (usually a large engine) for which conventional air flow measurement is impractical. This situation obviously did not pertain to the engine used in this test program since air flow rate was readily measured by a laminar flow element. A better reason to measure CO_2 concentration in the exhaust is to use the data as an indicator of combustion efficiency (higher CO_2 concentration indicates more complete combustion). However, it is also necessary to determine the amount of water vapor in the exhaust in order to complete the desired analysis, but no such measurement was performed in these tests. In any case, the measurement of CO_2 concentration and the subsequent carbon balance calculation were performed at the sponsor's request.

This calculation also involves concentrations of UBHC and CO, but, of course, CO_2 is the predominant carbon-carrying exhaust constituent and thus plays almost the total role in the exhaust gas part of the carbon balance. (For these tests, CO_2 concentration was in the range of 4 to 10%, or 40,000 to 100,000 parts per million; by comparison, maximum concentrations of UBHC and CO were approximately 3,000 and 6,000 ppm, respectively.) Accurate fuel consumption rate measurement and knowledge of the fuel carbon content are required for the other part of the carbon balance. Agreement between exhaust and fuel carbon is usually within 1 or 2% if the pertinent quantities have been accurately measured. Any discrepancy is usually due to an error in the CO_2 concentration measurement, since the fuel consumption rate and fuel carbon content are generally not subject to significant error. This is certainly true of these tests, where the fuel consumption measurement was known to be very accurate and repeatable, and fuel carbon content was precisely known from the complete fuel analysis shown in Appendix A.

Engine Speed: 2000 rpm

IMEP, psi

● 68
■ 82
▲ 96

Water In Fuel, Vol. %

Percent Change in CO Conc.

+160
+140
+120
+100
+ 80
+ 60
+ 40
+ 20
0
- 20
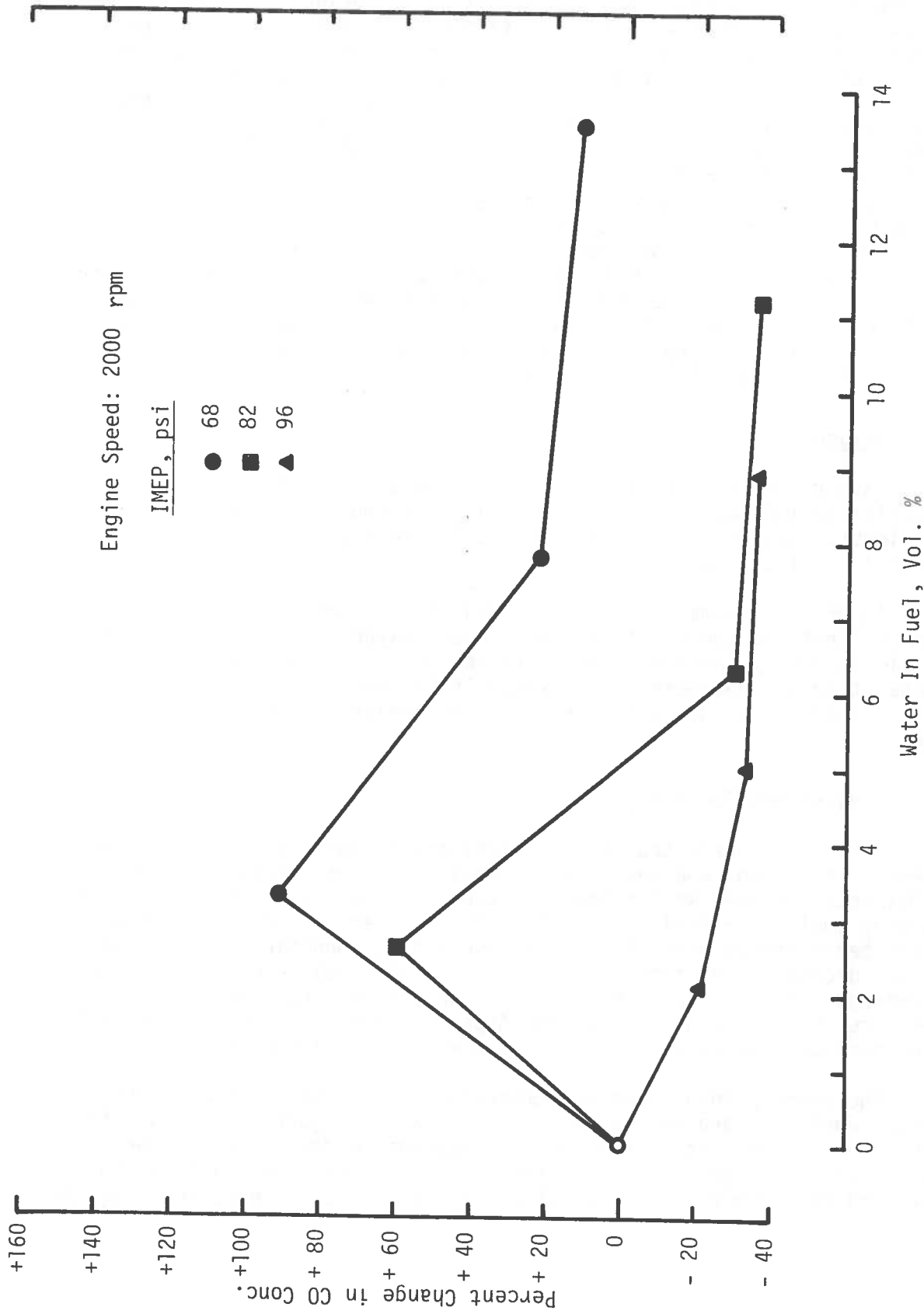- 40

0 2 4 6 8 10 12 14

FIGURE 3.22 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON CARBON MONOXIDE
CONCENTRATION AT 2000 REV/MIN--DYNATROL EMULSIFIER

and, in general, the largest decreases were obtained with the higher water percentages. However, the data are not as consistent in this regard as the data obtained with Daedalean emulsions.

3.9   Ignition Delay and Injection Timing

Another effect on engine performance which has been sometimes attributed to use of water-in-fuel emulsions is an increase in the ignition delay period (i.e., the time between the start of injection and the onset of combustion), which in turn necessitates an advance in injection timing in order to optimize power output under the given operating conditions. Some investigators report that under extreme conditions, such as when a high fuel-water content is being used, the ignition delay becomes so long that injection timing must be advanced by an amount sufficient to negate any decrease in NO_x that would ordinarily result from use of emulsified fuel. There is another consequence associated with this greatly advanced injection timing which bears upon the question of whether or not emulsified fuels are practical fuels for use in real-life diesel engines. Most laboratory research engines (including the CLR engine used in these tests) have an adjustment capability in their injection timing setting which is great enough to permit best power timing to be obtained even under conditions involving extremely long ignition delays. However, production engines usually have a much more limited range in the adjustment of injection timing; typically, 6° to 8° Crank Angle (CA) is the maximum injection advance that can be obtained without disassembling the pump in order to make an internal adjustment.

A limited analysis of the effect of the various emulsified fuels on ignition delay and best power timing (BPT) of the CLR engine was performed. The analysis was limited by the fact that the desired data must be obtained by visual analysis of the photograph of the oscilloscope traces showing injector needle lift, cylinder pressure, and crankshaft timing marks. With more than 350 tests performed, this analysis assumed formidable proportions. Hence, it was decided to analyze the photographic records for two or three tests at each condition (with baseline and emulsified fuels), and it is these data that are discussed here. In regard to the accuracy of this visual analysis of the traces, it should be understood that the photographic record can only be read to approximately ± 1° CA since this is the approximate width of the trace. Further, the point of injector needle lift is oftentimes not "clean" since the needle bounces or jiggles slightly as it starts to open. This situation introduces a certain amount of subjectivity into the visual analysis; it is estimated that this situation introduces another uncertainty into these data which is equal to 0.5 to 1.0° CA. It was therefore decided to interpret variations of 1.5° CA or less in a given value as constituting essentially no real change.

At the 1000 rpm test conditions, where fuel water contents up to 20 and 23.5% were used from the Daedalean and Dynatrol devices respectively,

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The comments presented above are based upon 130 to 150 hours of engine operation on emulsified fuel. The results imply that short-term severe or catastrophic consequences did not occur in this particular engine. The question of whether or not the durability of modern production diesel engines would be substantially affected by use of emulsified fuels cannot and should not be inferred from these results.

4. SUMMARY AND CONCLUSIONS

The primary objective of this program was to define the possible consequences (both favorable and adverse) associated with the use of unstabilized water-in-fuel emulsions in diesel engines. The emulsified fuel was produced on-line with the engine by two prototype emulsification devices. A single-cylinder, four-stroke cycle engine was operated using baseline fuel and emulsions containing from 2 to 23.5% water by volume. Effects associated with use of the emulsions were determined by making detailed measurements of fuel consumption, engine operating parameters, and exhaust emissions as the engine was operated through a test sequence involving back-to-back runs with baseline fuel and emulsified fuel. Four to six tests were conducted at each engine speed-load operating condition with both baseline and emulsified fuel, and the results of the fuel consumption measurement were statistically analyzed to determine if observed changes in this parameter could be stated at a 90% confidence level. Gaseous emissions data were obtained during just one set of test runs for each emulsion-water concentration.

The results of these tests are summarized in Table 4.1. The range of values and average value of the percentage change in each parameter is tabulated for emulsified fuel produced by each of the devices. The changes shown for indicated specific fuel consumption (ISFC) represent only those points where the change was statistically established. The average change in each parameter includes both positive and negative contributions in those cases where both were present. The only exception to this approach is explained in the footnote to the table. Established reductions in ISFC were obtained at 10 to 18 test conditions with each emulsification device. It is interesting to note that, even though the two devices produced emulsified fuel by differerent methods and their physical relationship to the engine was likewise completely different, the trends in the data obtained during the two test series are generally the same, with the principal difference being the magnitude of the change. No adverse effects on engine operating characteristics were encountered at any of the test conditions. No abnormal wear was in evidence when the engine was torn down and visually inspected at the end of the program.

It is concluded that the principal benefits associated with the use of emulsified diesel fuel in the test engine are reduced specific fuel consumption at some operating conditions, together with an overall reduction in exhaust smoke density and oxides of nitrogen (NO_x) concentration. Adverse effects found are sometimes substantial increases in concentration of unburned hydrocarbons and carbon monoxide. Inspection of the data indicates that optimization of the water content of the emulsion to the particular engine operating condition might enhance the benefits and minimize the drawbacks outlined here.

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5. RECOMMENDATIONS

This program, like most, was a special-case situation involving a specific engine operating at specific test conditions. Therefore, the results should not be generalized to a variety of engines operating under different conditions. However, these preliminary results are encouraging and lead to the following recommendations:

1. A program similar to this one should be conducted with a multi-cylinder, modern production diesel engine, preferably of a type and configuration used by the U.S. Coast Guard. The engine should be substantially smaller than the large, medium-speed main propulsion diesels used in the larger classes of Coast Guard cutters. This approach will minimize the program cost and constitutes the next step in a logical progression to use emulsified fuel in the larger engines.

2. If emulsified fuel (with water content optimized to the range of engine operating conditions) produces overall favorable effects in the fuel consumption and emission characteristics of the multi-cylinder engine, the design and construction of a shipboard system to produce and handle emulsified fuel for an in-service Coast Guard engine should be undertaken. The final working prototype of this fuel system should be checked out in the laboratory in preparation for its installation onboard a Coast Guard vessel.

3. The emulsification system should be installed on a vessel powered by the same type of engine used in the laboratory evaluation. Following installation and checkout, the system should be subjected to a shipboard demonstration consisting of two parts. The first part should involve measurement of engine performance and emission character- istics to ascertain that the emulsified fuel produces essentially the same effects with the in-service engine as it did with the laboratory engine. The second part of this demonstration should involve a long-term (minimum of six to twelve months) field trial in order to assess the full consequences arising from use of emulsified fuel in the engine and to determine areas where the design and performance of the emulsification system can be improved.
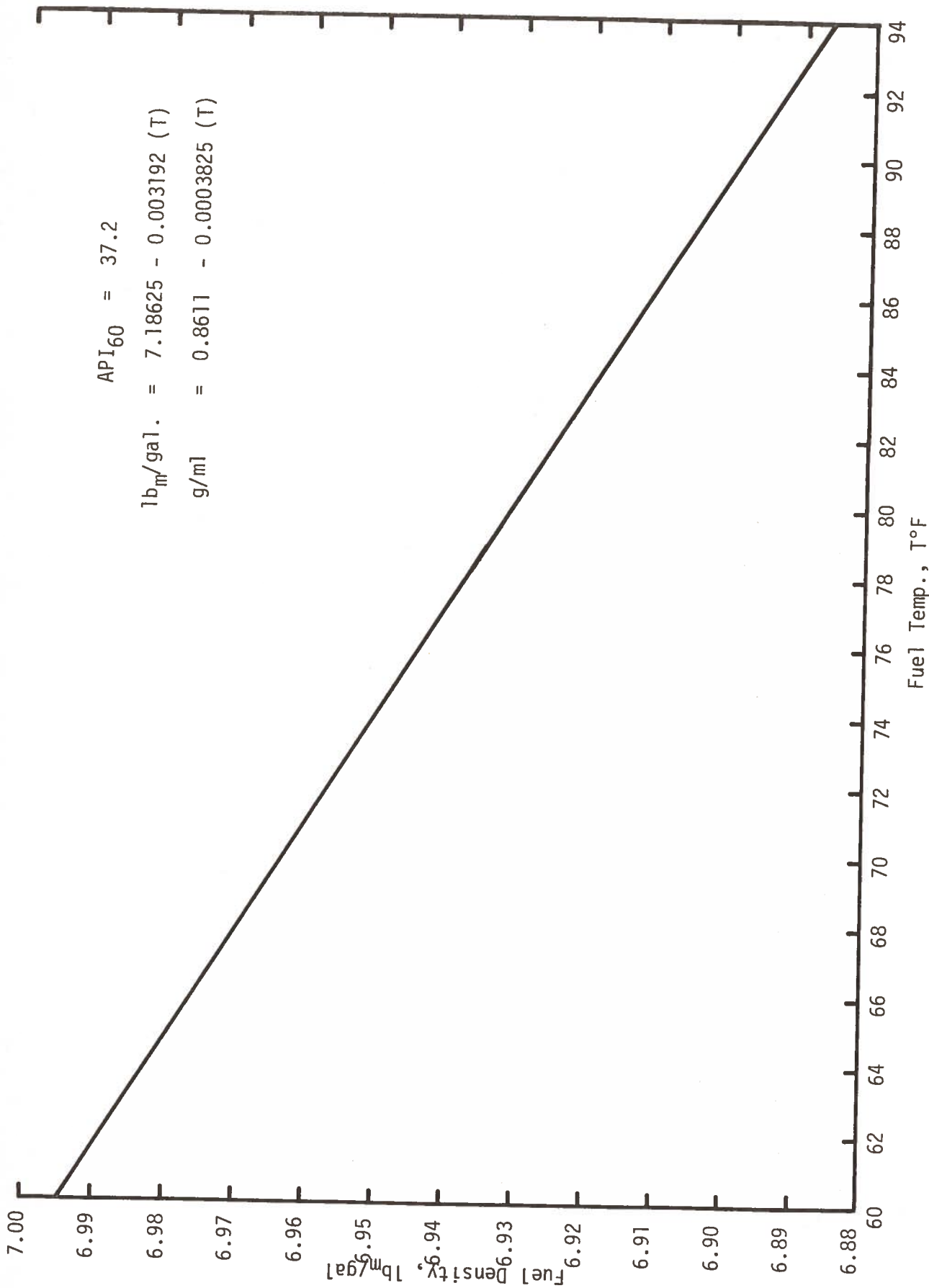
APPENDIX A

Baseline Diesel Fuel Analysis

FIGURE A-1 - BASELINE DF-2 FUEL DENSITY AS A FUNCTION OF FUEL TEMPERATURE

$$API_{60} = 37.2$$

$$lb_m/gal. = 7.18625 - 0.003192 \ (T)$$

$$g/ml = 0.8611 - 0.0003825 \ (T)$$

Fuel Temp., T°F

Fuel Density, lb_m/gal

A-3

APPENDIX B

Supplementary Engine Performance
and Emissions Data

TABLE B-2. SUMMARY OF ENGINE PERFORMANCE, SMOKE, AND GASEOUS EMISSIONS DATA--DYNATROL EMULSIFIER

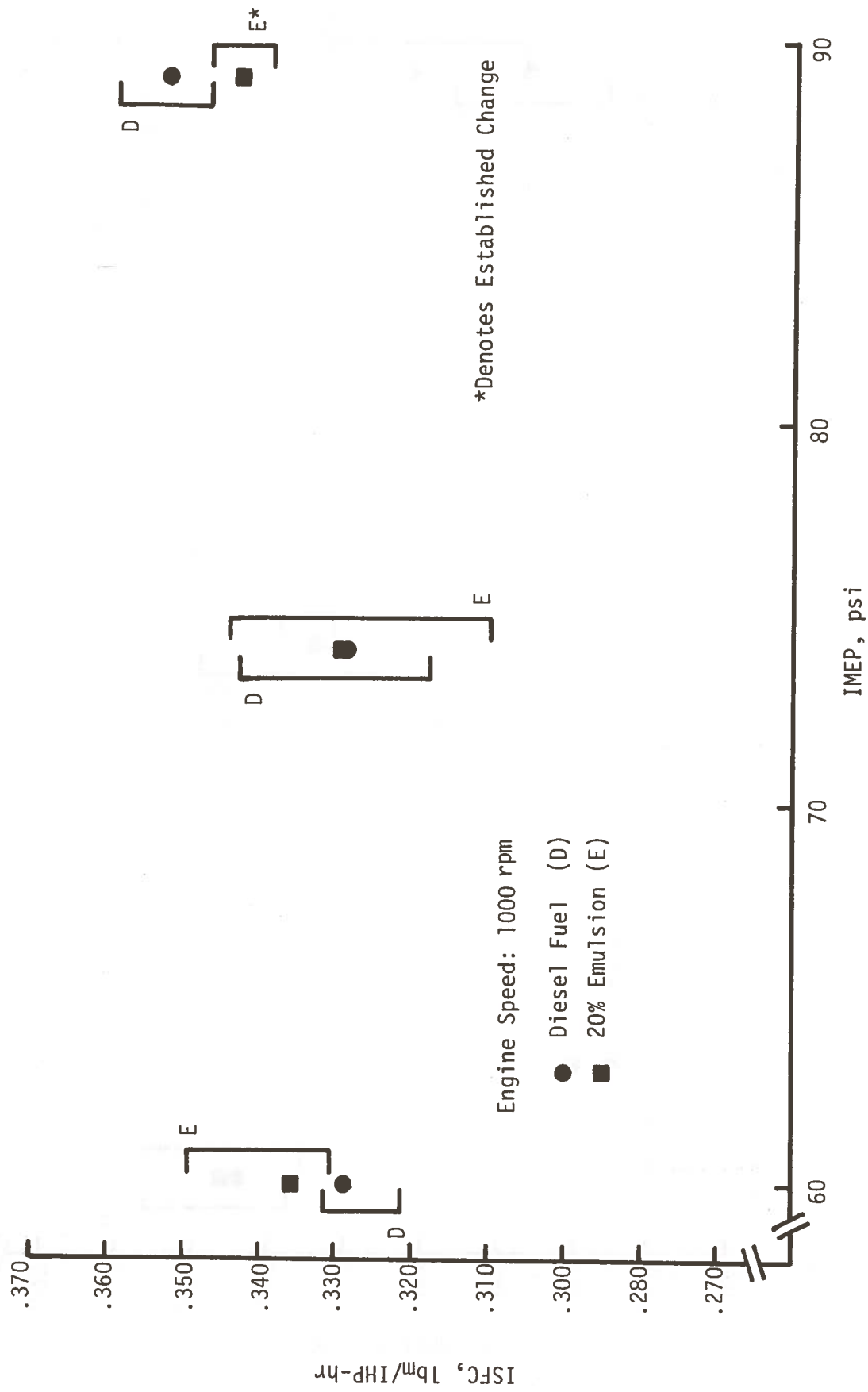| Engine Rev/Min	IMEP psi	H₂O in Fuel Vol %	ISFC lbm/IHP-hr	% Change	Smoke Bosch No.	% Change	Exhaust Temp. °F	% Change	NOx ppm	% Change	U3HC ppmC	% Change	CO ppm	% Change	CO2 %	% Change	O2 %	% Change
1000	60	0	.3156		0		442		690		1424		631		4.63		13.12	
		6.4	.3094	-2.0*	0	--	439	-0.7	500	-27.5	1888	+32.6	786	+24.6	4.48	-3.2	13.00	-0.9
		0	.3159		0.2		437		670		1640		616		6.49		11.50	
		14.4	.3150	-0.3	0.1	--	433	-0.9	450	-32.8	1760	+7.3	989	+60.6	6.33	-2.5	11.25	-2.2
		0	.3185		0		442		665		1520		631		4.77		14.25	
		23.5	.3266	+2.5*	0.7	--	424	-4.1	270	-59.4	1856	+22.1	1714	+171.6	4.55	-4.6	14.25	0
	75	0	.3222		0.7		534		1110		1280		586		5.92		12.50	
		5.2	.3184	-1.2*	0.6	-14.3	528	-1.1	915	-17.6	1520	+18.8	586	0	5.84	-1.4	12.37	-1.0
		0	.3267		1.3		532		870		1440		557		6.16		11.25	
		12.0	.3193	-2.3*	0.8	-38.5	525	-1.3	660	-24.1	1800	+25.0	616	+10.6	6.33	+2.8	13.25	+17.8
		0	.3255		1.1		529		795		1536		586		6.08		12.50	
		20.2	.3224	-1.0	0.5	-54.5	520	-1.7	440	-44.7	2192	+42.7	1097	+87.2	6.08	0	12.25	-2.0
	90	0	.3343		2.3		650		960		1280		852		7.36		9.75	
		4.3	.3328	-0.4	2.1	-8.7	640	-1.5	860	-10.4	1344	+5.0	835	-2.0	7.27	-1.2	9.75	0
		0	.3392		2.7		647		821		1720		868		7.81		10.75	
		10.0	.3327	-1.9	2.4	-11.1	634	-2.0	730	-11.0	2200	+27.9	936	+7.8	8.08	+3.5	10.50	-2.3
		0	.3365		3.0		656		880		1888		1079		7.72		10.25	
		17.0	.3321	-1.3*	2.7	-10.0	643	-2.0	520	-40.9	2016	+6.8	1439	+33.4	7.63	-1.2	10.25	0
2000	68	0	.2880		0.8		603		630		928		557		5.29		12.37	
		3.3	.2890	+0.3	1.4	+75.0	617	+2.3	540	-14.3	1856	+100.0	1061	+90.5	5.37	+1.5	11.87	-4.0
		0	.2920		0.8		606		655		1820		631		5.37		13.00	
		7.8	.2879	-1.4*	0.6	-25.0	608	+0.3	400	-38.9	1680	-7.7	770	+22.0	5.37	0	12.25	-5.8
		0	.2879		1.0		595		500		1216		676		5.53		11.50	
		13.5	.2862	-0.6	0	--	584	-1.8	360	-28.0	1168	-3.9	754	+11.5	5.37	-2.9	11.25	-2.2
	82	0	.2985		2.1		723		835		672		971		6.92		11.50	
		2.6	.2969	-0.5	1.6	-23.8	719	-0.6	930	+11.4	1552	+131.0	1550	+59.6	6.92	0	11.37	-1.1
		0	.3066		2.5		739		930		2000		1154		7.01		10.75	
		6.3	.3000	-2.2*	2.2	-12.0	740	+0.1	655	-29.6	1920	-4.0	802	-30.5	7.27	+3.7	11.25	+4.7
		0	.3013		2.2		728		680		1312		1482		7.01		10.50	
		11.2	.2949	-2.1*	1.4	-36.4	716	-1.6	560	-17.6	1296	-1.2	936	-36.8	7.18	+2.4	9.88	-5.9
	96	0	.3296		5.0		924		800		1728		2375		8.95		8.50	
		2.1	.3166	-3.9*	4.6	-8.0	905	-2.1	825	+3.1	1664	-3.7	1865	-21.5	8.85	-1.1	8.37	-1.5
		0	.3312		5.5		935		690		2980		3027		9.04		8.50	
		5.0	.3247	-2.0*	4.6	-16.4	914	-2.2	800	+15.9	3040	+2.0	1997	-34.0	8.95	-1.0	7.75	-8.8
		0	.3337		5.5		934		540		1936		4382		9.04		8.25	
		8.9	.3236	-3.0*	4.0	-27.3	870	-6.9	680	+25.9	1600	-17.4	2772	-36.7	8.95	-1.0	8.12	-1.6

* Change Statistically Established at 90% Confidence Level

FIGURE B-2 - EFFECT OF 20% WATER-IN-FUEL EMULSION ON ENGINE SPECIFIC
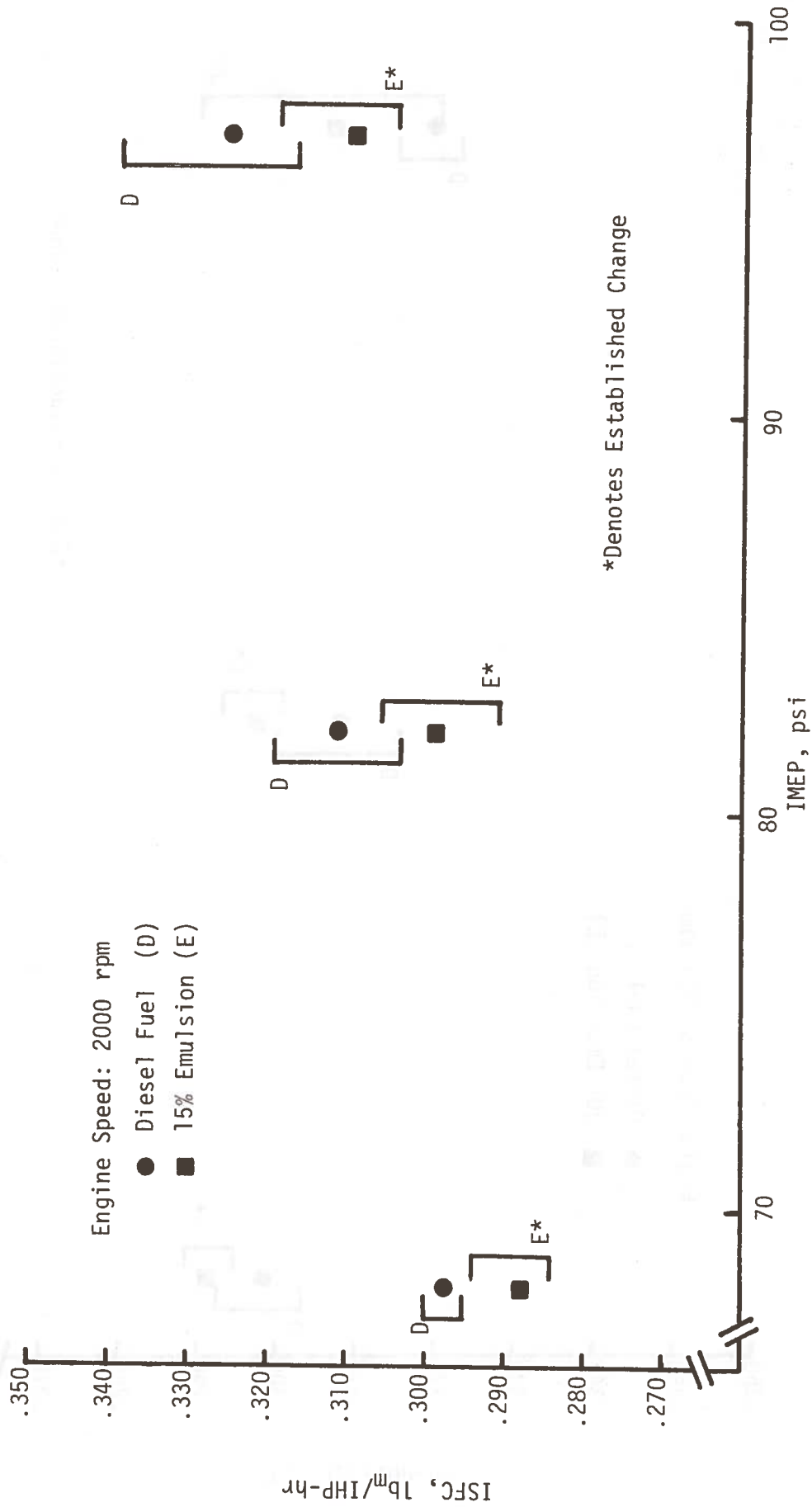FUEL CONSUMPTION AT 1000 REV/MIN--DAEDALEAN EMULSIFIER

*Denotes Established Change

Engine Speed: 1000 rpm

● Diesel Fuel (D)
■ 20% Emulsion (E)

IMEP, psi

ISFC, lbm/IHP-hr

FIGURE B-4 – EFFECT OF 15% WATER-IN-FUEL EMULSION ON ENGINE SPECIFIC
FUEL CONSUMPTION AT 2000 REV/MIN--DAEDALEAN EMULSIFIER

Engine Speed: 2000 rpm

● Diesel Fuel (D)
■ 15% Emulsion (E)

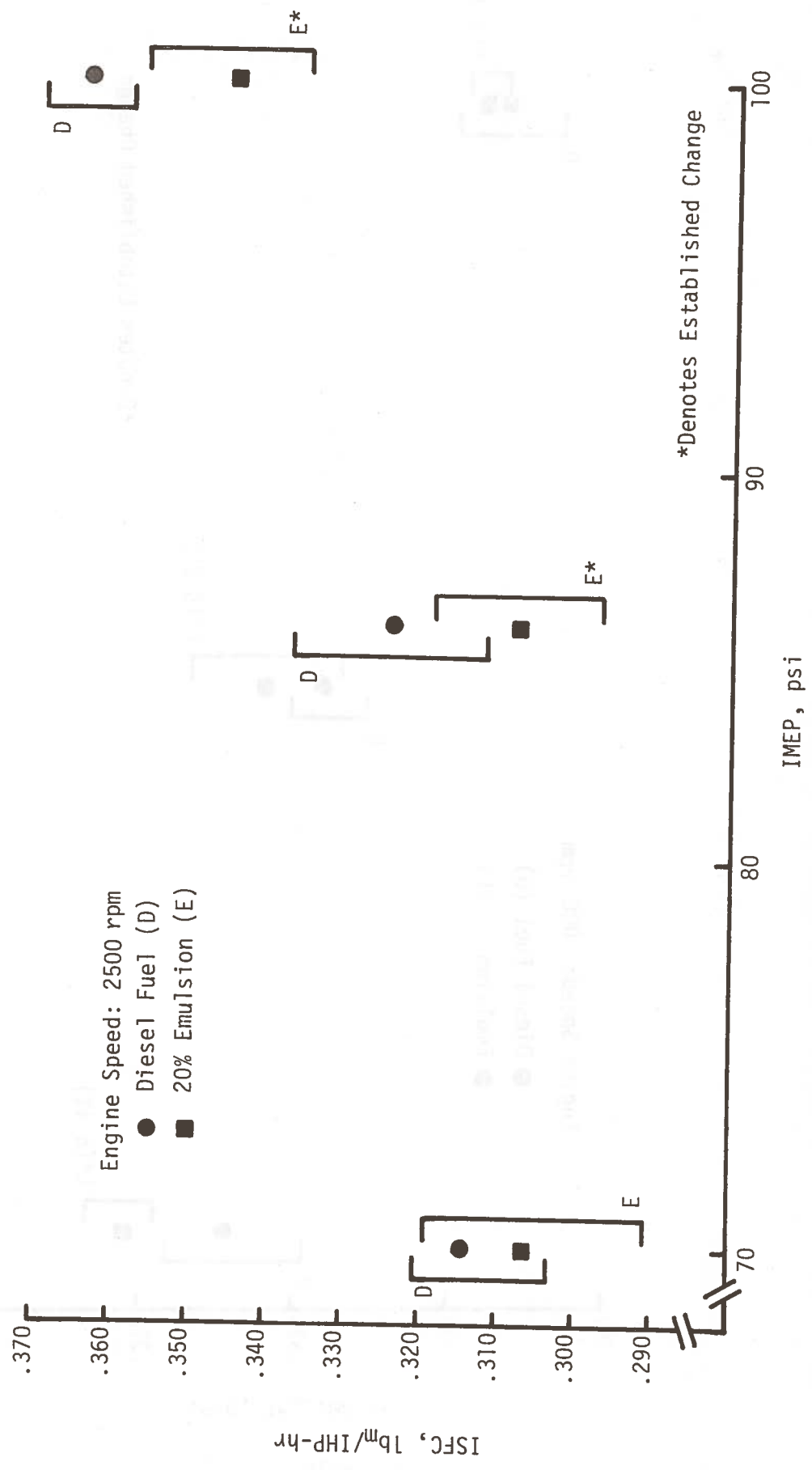*Denotes Established Change

IMEP, psi

ISFC, lb$_m$/IHP-hr

FIGURE B-6 - EFFECT OF 20% WATER-IN-FUEL EMULSION ON ENGINE SPECIFIC
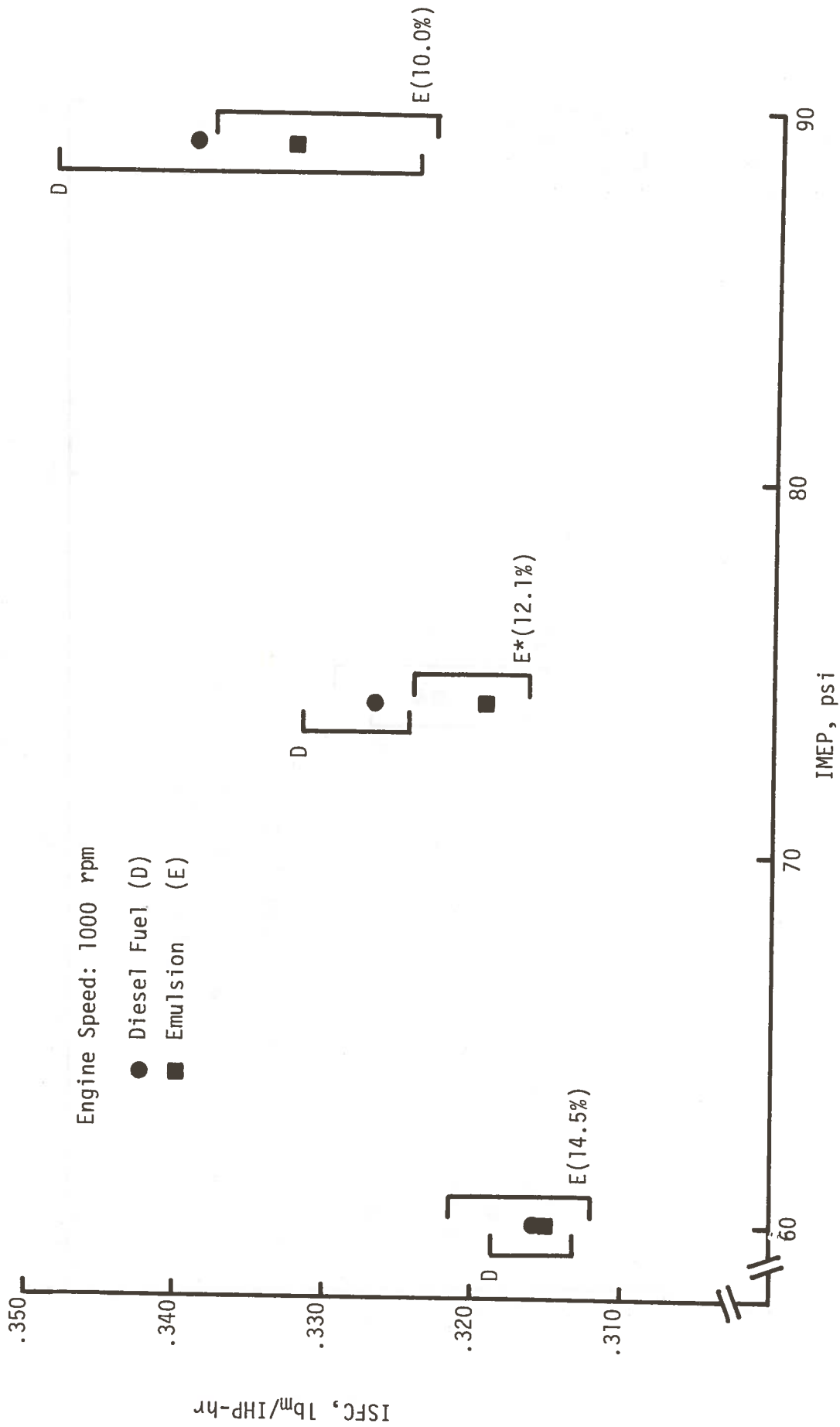FUEL CONSUMPTION AT 2500 REV/MIN--DAEDALEAN EMULSIFIER

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FIGURE B-8 - EFFECT OF EMULSIFIED FUEL ON ENGINE SPECIFIC FUEL
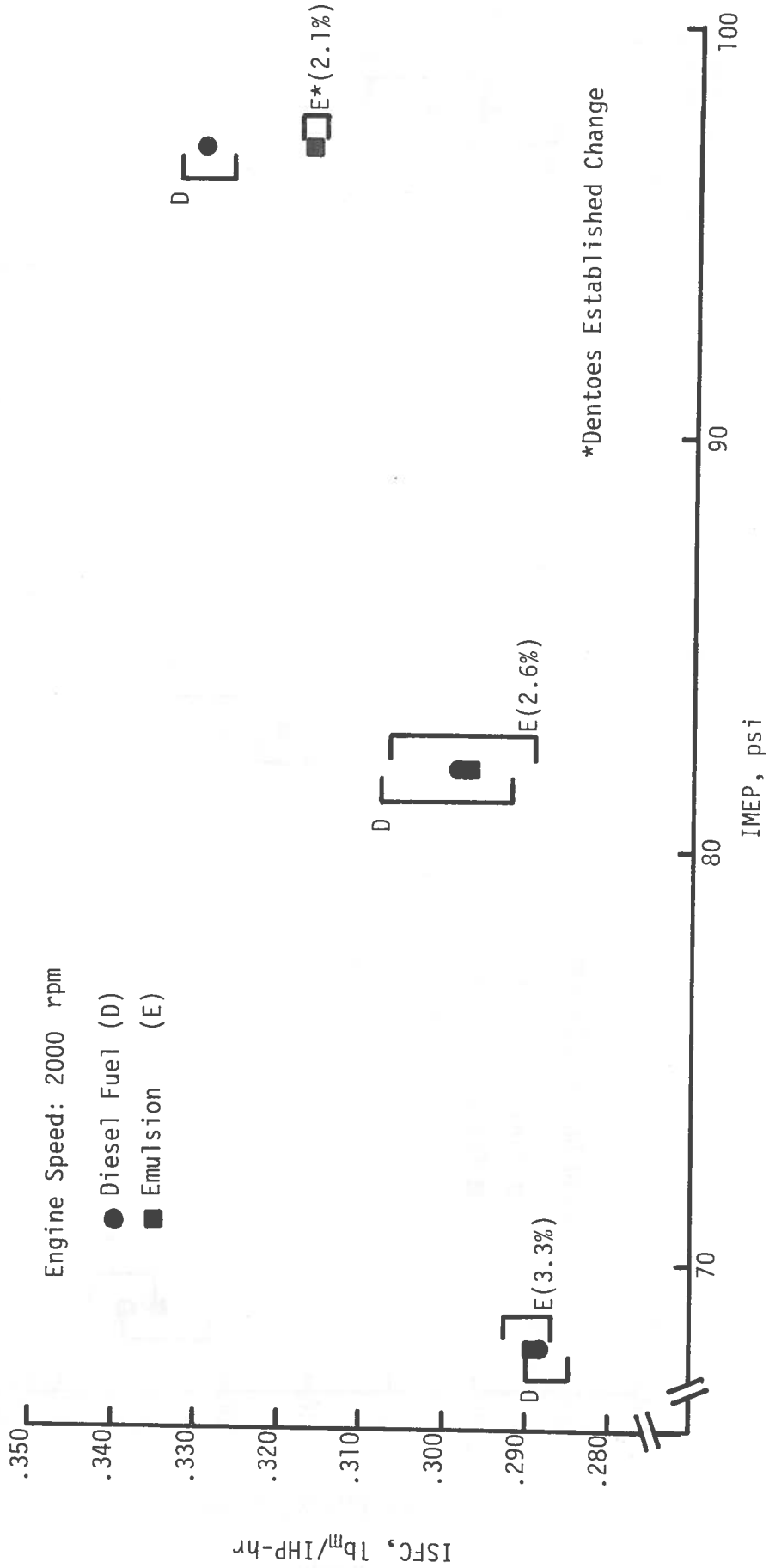CONSUMPTION AT 1000 REV/MIN--DYNATROL EMULSIFIER

FIGURE B-10 - EFFECT OF EMULSIFIED FUEL ON ENGINE SPECIFIC FUEL
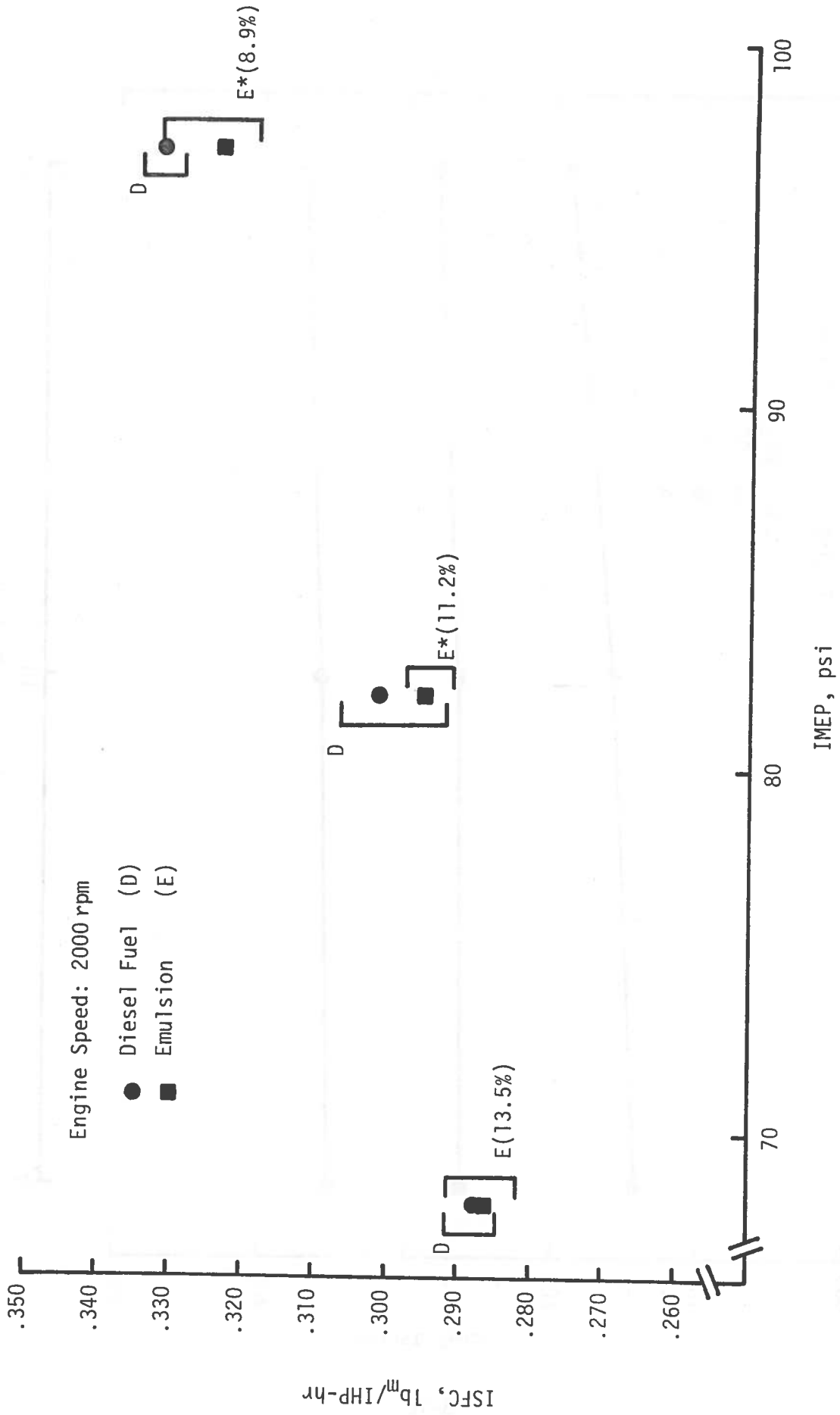CONSUMPTION AT 2000 REV/MIN--DYNATROL EMULSIFIER

FIGURE B-12 -EFFECT OF EMULSIFIED FUEL ON ENGINE SPECIFIC FUEL CONSUMPTION
AT 2000 REV/MIN--DYNATROL EMULSIFIER
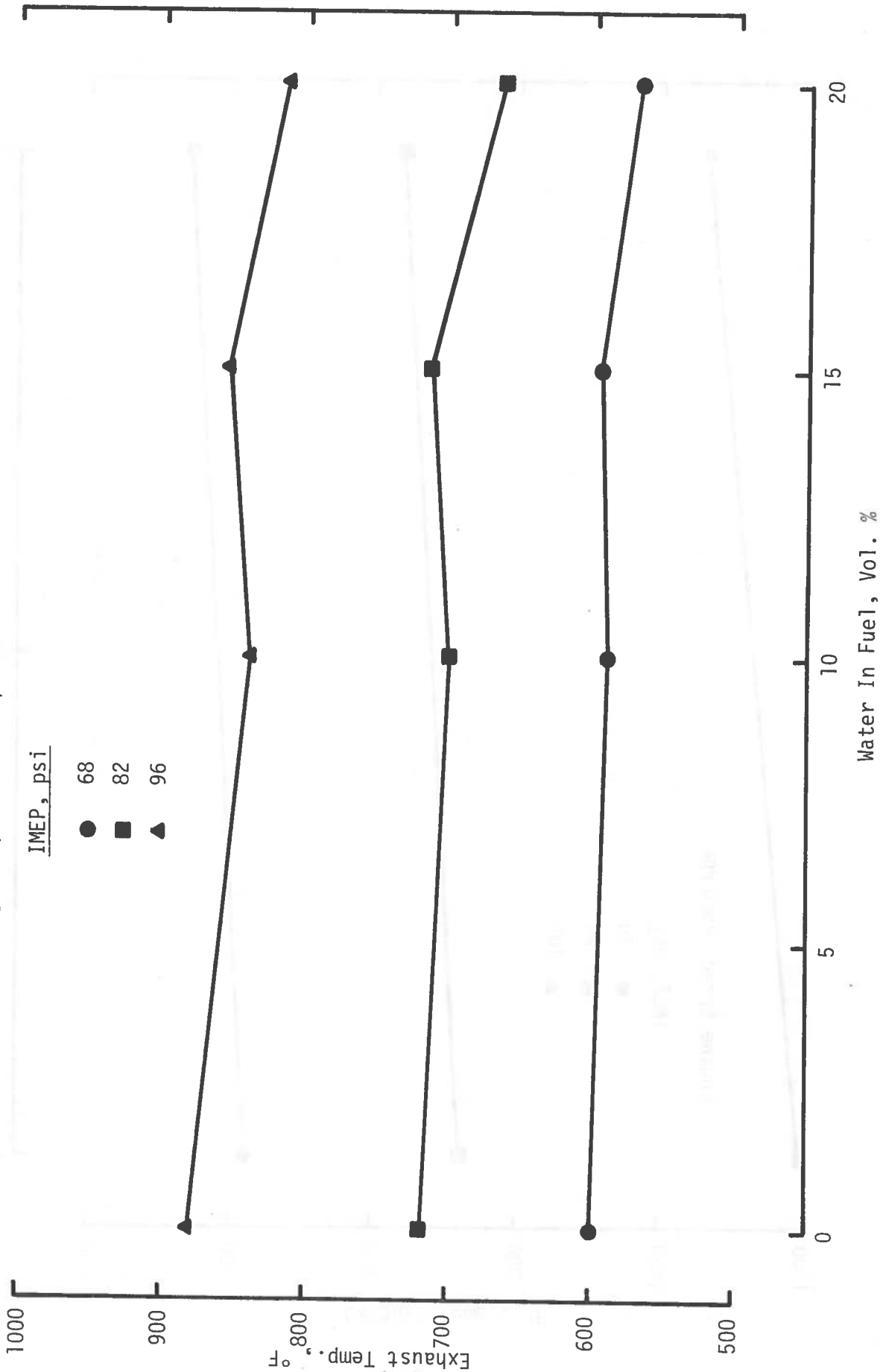
Engine Speed: 2000 rpm

FIGURE B-14 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON EXHAUST TEMPERATURE
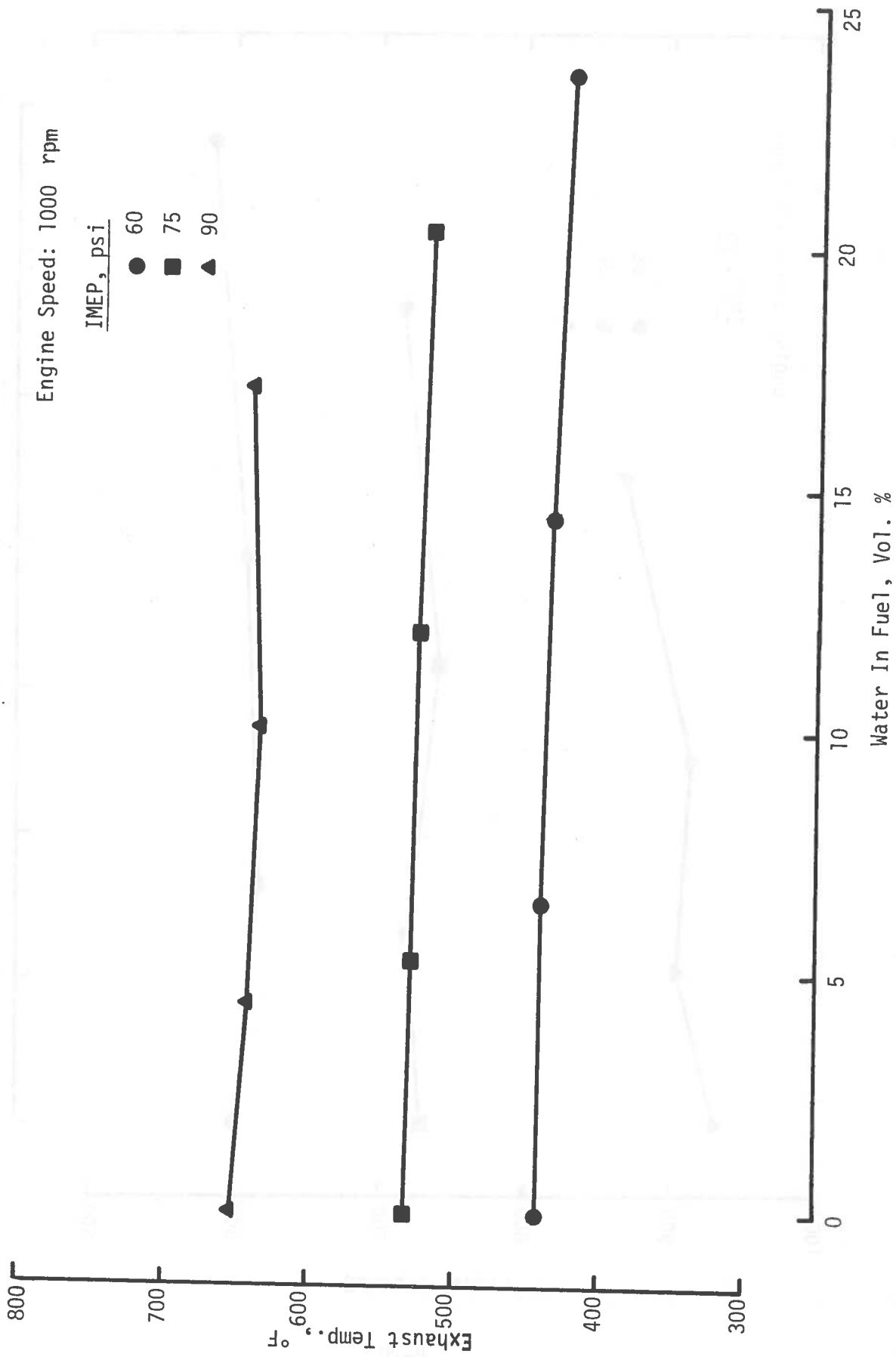AT 2000 REV/MIN--DAEDALEAN EMULSIFIER

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FIGURE B-16 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON EXHAUST TEMPERATURE
AT 1000 REV/MIN--DYNATROL EMULSIFIER

APPENDIX C

REPORT OF INVENTIONS

The work performed under this contract produced no new inventions. However, a promising technique for improving the fuel economy and lowering the oxides of nitrogen and smoke emissions from diesel engines is described. This technique utilizes water emulsified into the diesel fuel to the engine. Although the tests reported on here were performed with a single-cylinder laboratory diesel engine, the methods described are applicable to diesel engines in general, though the same results may or may not be obtained.

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10. <u>Ibid</u>.