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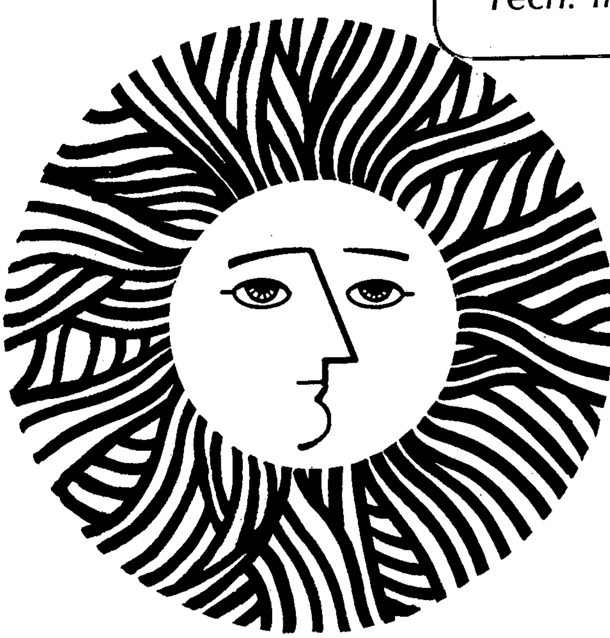

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DISCLAIMER

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This work was supported through the U.S. Department of Energy under Contract No. DE-AC03-76SF00098, by the U.S. Department of Transportation MARAD Contract No. MA-80-SAC-01859 with Transamerica Delaval, Inc., and by Transamerica Delaval, Inc.

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ABSTRACT

Particulate concentrations from a medium-speed, 2500 kW (3400-hp) diesel engine have been measured for diesel No. 2 reference fuel and two high viscosity fuels. The engine emits about 0.20 gm/bhp-hr on diesel No. 2 and about 0.65 gm/bhp-hr for both 3500 and 5000 Redwood viscosity residual fuels. Slightly higher particulate levels were observed at 100% load than at 75% or 50% load with the diesel No. 2 fuel only. Water emulsified residual fuels (without surfactant) at 0%-12% water addition (by volume) and 2-5, 5-10, and 10-20 micron droplet diameters were evaluated in this test matrix. No effects on particulate concentrations were detected as a result of different ranges of droplet diameter. Contrary to what might have been expected, particulate formation with 12% water addition was higher than with 4% water addition or neat 5000 Redwood fuel.

INTRODUCTION

Combustion equipment manufacturers and researchers have investigated the potential advantages of water injected into combustion systems since late in the eighthteenth century.[1] Originally, water addition was desirable for lowering operating system temperatures. More recently, however, Kopa, et al.[2] suggested that water addition would reduce combustion generated NO_x. NO_x production has been found to be markedly reduced with the presence of water in compression ignition engines.[3-7] A slight decrease in specific fuel comsumption with water addition has also been observed.

About 25 years ago Russian researchers[8] postulated that small diameter water droplets dispersed in fuel would improve fuel atomization. This occurs by the vaporization of water inside the fuel droplet preceding fuel vaporization. They theorized that the vaporizing water would shatter the fuel droplet thereby increasing the surface area available for evaporation. Several bench experiments have verified this claim.[5,8,9] Results in engines have also substantiated this theory.[3,4,7]

Transamerica Delaval, Inc.* with partial support from the Maritime Administration (MARAD) of the Department of Transportation evaluated water emulsified heavy residual fuels in the six-cylinder version of their Enterprise medium-speed diesel engine line. As part of the program, Lawrence Berkeley Laboratory (LBL) collected particulate samples

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*Nitrogen oxide emission and specific fuel consumption results of the present work can be found in the final report of the U.S. Department of Transportation MARAD Contract No. MA-80-SAC-01859 with Transamerica Delaval, Inc.

for mass measurements. Delaval tested diesel No. 2 reference fuel and three residual fuels at 4 levels of water addition, 3 droplet diameters, and at 50%, 75%, and 100% engine load conditions. The purpose of this program was to pinpoint the most effective level of water emulsification and water droplet diameter for each of the fuels in accomplishing the following:

1.) reduce specific fuel consumption,

2.) reduce particulate emissions, and

3.) reduce NO_x emissions.

EXPERIMENTAL METHOD

The engine used in these tests is briefly described in Table I. Three residual fuels with viscosities of 1500*, 3500, and 5000 Redwood seconds** were compared to diesel No. 2 as the reference fuel. Except for diesel No. 2 which is sufficiently pumpable, all the fuels were heated in order that the kinematic viscosity was nearly 70 Saybolt Universal Seconds (13.0×10^{-6} m^2/sec).

The residual fuels were tested without water and with 4%, 8%, and 12% by volume addition of water. Another important parameter varied was the water droplet diameter emulsified in the fuel. Most of the emulsified fuels were held inside the 2-5, 5-10, or 10-20 micron droplet size

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*Particulate measurements on the 1500 Redwood viscosity fuel were not made.

**Redwood seconds viscosity is nearly the same as Saybolt Universal Seconds. Therefore, 1500 Redwood = 0.00034 sq meters/sec, 3500 Redwood = 0.00075 sq meters/sec, and 5000 Redwood = 0.00112 sq meters/sec.

ranges. The diameter was verified by photomicrographs at 1000 power.

The emulsor unit used in this study was manufactured by the Gaulin Corp. This prototype, called the Low Energy Hydroshear, can provide water flow rates up to 630 cc/sec (10 gal/min) with a pressure drop of 1.9 MPa (280 psig) for 2-5 micron diameter droplets and a 70 kPa (10 psig) drop for producing 10-20 micron droplets. In the investigation reported here, 20 cc/sec (0.3 gal/min) was the maximum water flowrate required. No surfactant was required since the emulsified fuel was immediately injected into the engine.

A schematic of the particulate sampling apparatus is shown in Figure 1. The sampling probe in the exhaust stack contains 15-64 mm. diameter holes spaced so as to provide a mean sample of the exhaust. Approximately 0.05% of the exhaust gas is mixed with ambient air in proportions of 1 part exhaust gas to 10-20 parts air. At these dilution ratios, the temperature at the filter was lower than 50^{o}C. A portion of this well mixed, diluted exhaust sample is then passed through a filter by a constant mass flowrate (1 gm/sec) vacuum pump. The remainder of the diluted exhaust is vented to the atmosphere. No attempt was made to sample isokinetically because it is not an important consideration for collection submicron particles.[10]

The level of dilution achieved was measured in two ways:

1.) direct measurement of the flowrate through the exhaust probe and the flowrate of the dilution air.

2.) comparison of the NO_x concentration in the exhaust stack with the NO_x concentration in the diluted exhaust sample.

Unfortunately, measurement of the exhaust flowrate with the square-edged orifice shown in Figure 1 was not satisfactory. With no flow the pressure gauge indicated a pressure difference across the orifice of about 2.5 cm of water pressure which is on the order of half of the full scale reading. At the sampling probe location downstream of the turbocharger, large pressure fluctuations existed. Some dynamic effect as a result of these pressure fluctuations appeared to be responsible for pressure differences across the orifice indicating a different flowrate than under steady flow, steady pressure calibration conditions. Because of these problems, all data reduction was based on the NO_x technique for determining dilution ratio.

The samples were collected on teflon coated filters rated at two micron pore size obtained from the Ghia Corporation, Pleasanton, CA. The 37 mm diameter filters were mounted in a polyester frame by Ghia. These filters are compatible with an automated device developed at LBL for measuring aerosol mass. The beta gauge[11] operates by measuring the attenuation of beta particles caused by the filter substrate and the particles collected on the filter. The filter is placed between a radioactive source, namely ^{147}Pm, and a detector. The difference in attenuation before and after particle collection yields mass. The precision of this instrument is +/-5 micrograms/cm^{2}* with a maximum loading of about 200 micrograms/cm^{2}. Careful measurements with a microbalance can give slightly better precision. However, the beta gauge has several signigicant advantages which have proven it to be a powerful tool in

*The precision is +/-3 micrograms/sq cm per individual measurement. But, both a tare and final measurement are required. This results in a +/-5 micrograms/sq cm total uncertainty.

this program:

1.) Over 100 filters/8 hour day can be measured by the automated beta gauge.

2.) Filter handling, storage, removal, and installation are greatly facilitated by the polystyrene frame. Also, the risk of contamination is minimized.

3.) The teflon coated filters absorb a negligible amount of water making desiccation of the filters unnecessary.

RESULTS

The data from the entire test matrix is summarized in Table II. The results are separated by fuel type, % engine load, % water addition and water droplet diameter. Note that injection timing was a variable in the test matrix. However, insufficient comparative data are available to quantify the effect of injection timing. Therefore, the statistical analysis of the other variables has been carried out irrespective of injection timing.

Figures 2-6 graphically depict the reduced data. Each bar represents the average of all samples taken at each point. The vertical line through the bar indicates the 90% confidence interval for the mean of that measurement, that is, the range in which the true mean lies at 90% assuredness. Taking into consideration the variability of these measurements and the number of samples collected, the true mean of each point can be estimated to be within about 25% of the measured mean. Thus, unless a difference greater than 25% exists between two points being compared, these measurements may not reveal a significant difference.

The diesel No. 2 reference fuel emitted approximately 0.20 gm/bhp-hr of particulate. Particulate formation at 100% load was higher than at either 50% or 75% load (statistically significant at the 90% confidence level). This difference is depicted in Figure 2.

Figure 2 also shows comparisons between diesel No. 2 reference and two residual fuels (with no water addition). The 3500 Redwood and 5000 Redwood viscosity fuels were indistinguishable in particulate formation. However, these residual fuels generate about 3.5 times as much particulate as the diesel No. 2 reference fuel, i.e., approximately 0.65 gm/bhp-hr. No trends as a function of engine load were observed for either residual fuel.

The percent water addition ranged from 0%-12% by volume in both the 3500 Redwood and 5000 Redwood viscosity fuels. Figure 3 shows the particulate levels at 0%, 4%, 8%, and 12% water addition for 3500 Redwood fuel; Figure 4 shows the same for 5000 Redwood fuel. The only statistically significant result is seen in Figure 4. At all load conditions with 12% water addition, more particulate is emitted than with 0% water addition. Moreover, the fuels containing 12% water formed more particulate than fuel containing 4% water at 50% and 75% loads.

The diameter of the water droplets added to the fuel was also varied. Figures 5 and 6 indicate no trends in particulate concentration as a function of water droplet diameter for either the 3500 or 5000 Redwood fuels.

DISCUSSION

Ultrachem Corp.[12] has taken particulate samples of a Transamerica Delaval DSRV-16-4 engine which is of the same family as the DSR-46 engine used in the present work. The data from both analyses on diesel No. 2 fuel are in good agreement. Figure 7 shows that Ultrachem reported about 30% fewer particulates than the present study. Note that both measurements show that particulate loading is maximized at 100% load and minimized at 75% load.

Hare and Bradow[13] reported results found on heavy-duty, high-speed diesels operating on diesel No. 2 fuel. The two-stroke and four-stroke engines emitted approximately 1.75 and 1.0 gm/bhp-hr particulate, respectively. This is in excess of five times as much as that produced by Delaval's medium-speed engine. Possibly this is a result of the longer residence times in the medium-speed engine allowing for more complete soot particle burnout.

Other researchers[3-7,14] have reported significant advantages when using water addition in compression ignition engines. Sizable reductions in both particulate and NO_x emissions have been claimed. However, the bulk of these data were collected at much higher water/fuel ratios than those studied here. Greeves, et al.,[3] found that at water/fuel ratios less than 20%, smoke levels (indicative of particulate concentration) were higher than with dry fuels in a high-speed, naturally aspirated, automotive type diesel engine. This may corroborate evidence found in this study. But on the other hand, it may be tenuous to compare results obtained in the automotive type engine with the medium-speed engine. Other researchers[4,7] have found smoke reductions with water/fuel ratios around 50% in medium speed diesels. These reductions over dry fuels were more evident at part load conditions.

The emulsified fuels did not meet particulate reduction goals. Since a somewhat limited range of water addition level and engine operating parameters was evaluated, it is possible that the combination of variables (eg. injection timing, % water addition) which would show the predicted soot reduction was not investigated.

CONCLUSIONS

1.) The Transamerica Delaval DSR-46 emits about 0.20 gm/bhp-hr on diesel No. 2 fuel and about 0.65 gm/bhp-hr on the two high viscosity residual fuels: 3500 and 5000 Redwood seconds viscosity.

2.) No statistically significant differences were observed as a result of varying the amount of water addition or water droplet diameter except that particulate concentrations were slightly higher at 12% water addition than at 0% or 4% water addition in the 5000 Redwood fuel.

ACKNOWLEDGEMENTS

This work was supported through the U.S. Department of Energy under Contract No. DE-AC03-765F00098, by the U.S. Department of Transportation MARAD Contract No. MA-80-SAC-01859 with Transamerica Delaval, Inc., and by Transamerica Delaval, Inc. The authors wish to thank J.J. Barich, Jr., A.R. Fleischer, and T. Hinricks of Transamerica Delaval for making the collection of particulates possible.

Thanks are also extended to the following LBL researchers: B.W. Loo for invaluable advice and support in aerosol collection techniques; R.C. Gatti for timely results with both filter weights and x-ray fluorescence measurements; and, R.F. Sawyer for technical advice and critical review of all stages of the program.

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TABLE I

DESCRIPTION OF ENGINE

MANUFACTURER: Engine and Compressor Division of Transamerica Delaval, Inc.

LOCATION OF MANUFACTURER: Oakland, CA

MODEL: DSR-46

CYCLE: Four Stroke Diesel

NUMBER OF CYLINDERS: Six

BORE X STROKE: 432 mm x 533 mm (17 in x 21 in)

COMPRESSION RATIO: 11.6:1

BMEP: 1.55 MPa (225 psi) at full load

SHAFT POWER: 2500 kW (3400 hp) at full load

SHAFT SPEED: 450 RPM

PRESSURE RATIO ACROSS TURBOCHARGER: 2.8 at full load

OTHER FEATURES: Intercooler after Turbocharger

Direct Fuel Injection

Two-piece Trunk-type Piston

Four Valves per Cylinder

TABLE II

SPECIFIC PARTICULATE EMISSION OF DELAVAL'S DSR-46, MEDIUM-SPEED DIESEL (gm/bhp-hr)

LOAD	% WATER	$D(10^{-6} m)$	DIESEL NO. 2	3500 REDWOOD	5000 REDWOOD
50% LOAD	0%	-	0.180, 0.169, 0.118, 0.147	0.607[1]	0.650, 0.567
	4%	2- 5		0.703[1], 0.741[1]	0.510[2], 0.652
	4%	5-10		0.673[1], 0.678[1], 0.622[1]	0.602[2], 1.035, 0.787
	4%	10-20		0.543[1]	1.021[2], 0.897[2], 0.663 0.617
	8%	2- 5			1.316, 1.197
	8%	5-10			0.806, 0.942
	8%	10-20			1.077[2], 0.825[2], 0.967, 1.114
75% LOAD	0%	-	0.164, 0.131, 0.137, 0.102, 0.111	0.702[1], 0.763[1]	0.580, 0.529
	4%	2- 5		0.713[1], 0.722[1]	0.737, 0.622
	4%	5-10		0.806[1], 0.690[1]	0.589[2], 0.491[2], 0.862, 0.621
	4%	10-20		0.765[1], 0.943[1]	0.605, 0.611
	8%	2- 5			0.758, 0.895
	8%	5-10			0.695, 0.798
	8%	10-20			0.744
	12%	2- 5			1.096
	12%	5-10		0.768[1], 0.889[1]	1,011,0.962
	12%	10-20		0.832[1], 0.997[1]	1.063, 0.844
100% LOAD	0%	-	0.252, 0.200, 0.290, 0.252	0.697[1], 0.647[1]	0.554, 0.574, 0.692, 0.721
	4%	2- 5		0.641[1], 0.779[1]	0.923[2], 1.073[2], 0.767[2], 0.697, 0.617
	4%	5-10		0.590[1], 0.706[1], 0.843[1]	0.530[2], 0.506[2], 0.597, 0.972
	4%	10-20			0.772[2], 0.934[2], 0.779, 0.639
	8%	2- 5		0.879[1], 0.613[1]	0.565, 0.902
	8%	5-10		0.676[1], 0.876[1]	0.437, 0.686, 0.588
	8%	10-20			1.002[2], 1.010[2], 0.543, 0.650
	12%	2- 5		0.791[1], 0.661[1]	0.928[2], 0.686[2], 0.968[2], 0,919, 1.124
	12%	5-10		0.613[1], 0.893[1]	1.046, 1.040
	12%	10-20		0.812[1], 0.732[1]	1.078[2], 1.000[2], 0.980, 0.831

NOTE: INJECTION TIMING IS 23° BTDC UNLESS NOTED OTHERWISE.

[1] 21° BTDC (STANDARD INJECTION TIMING)

[2] 25° BTDC

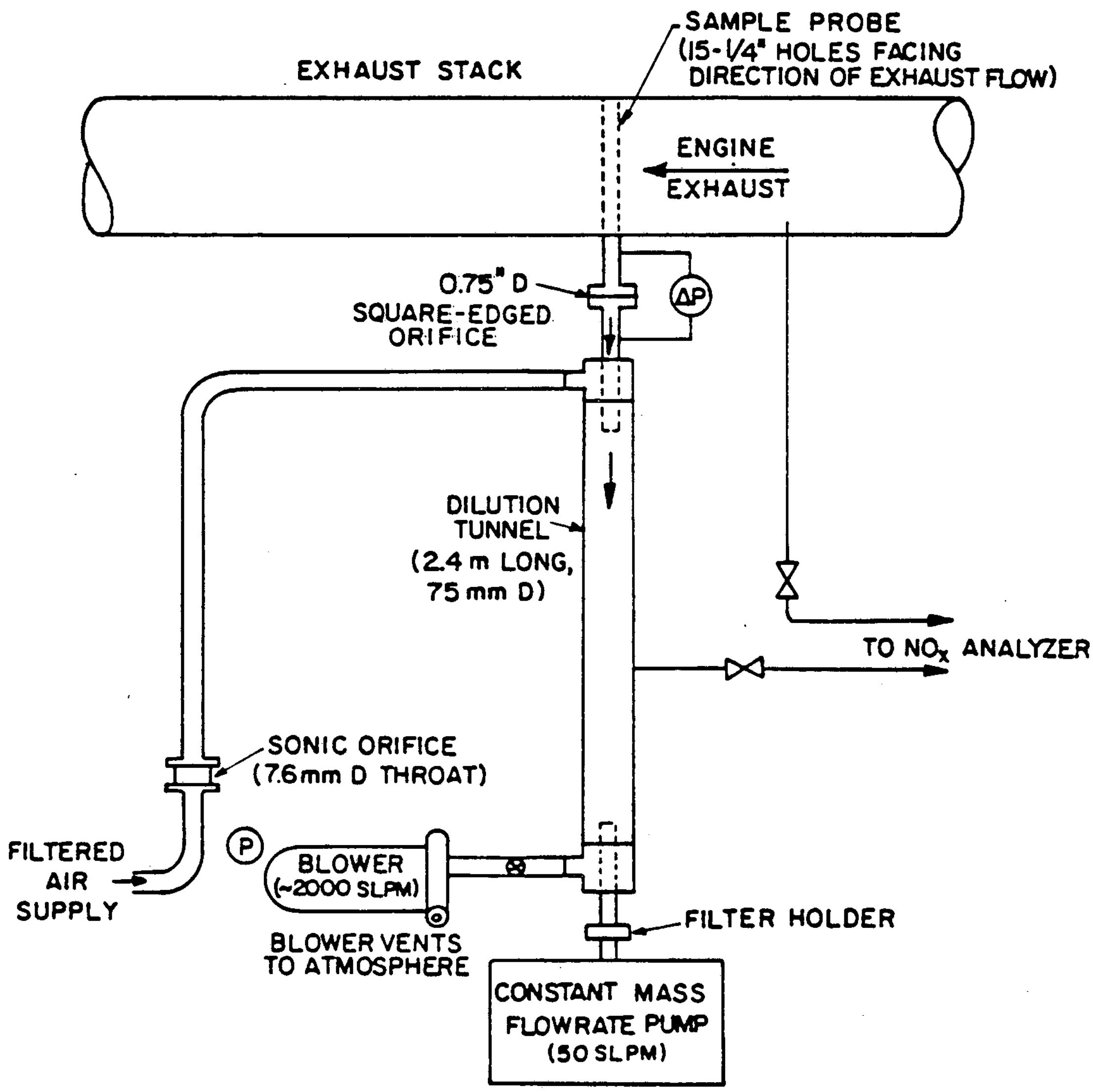

Figure 1. Schematic of Diesel Particulate Sampler

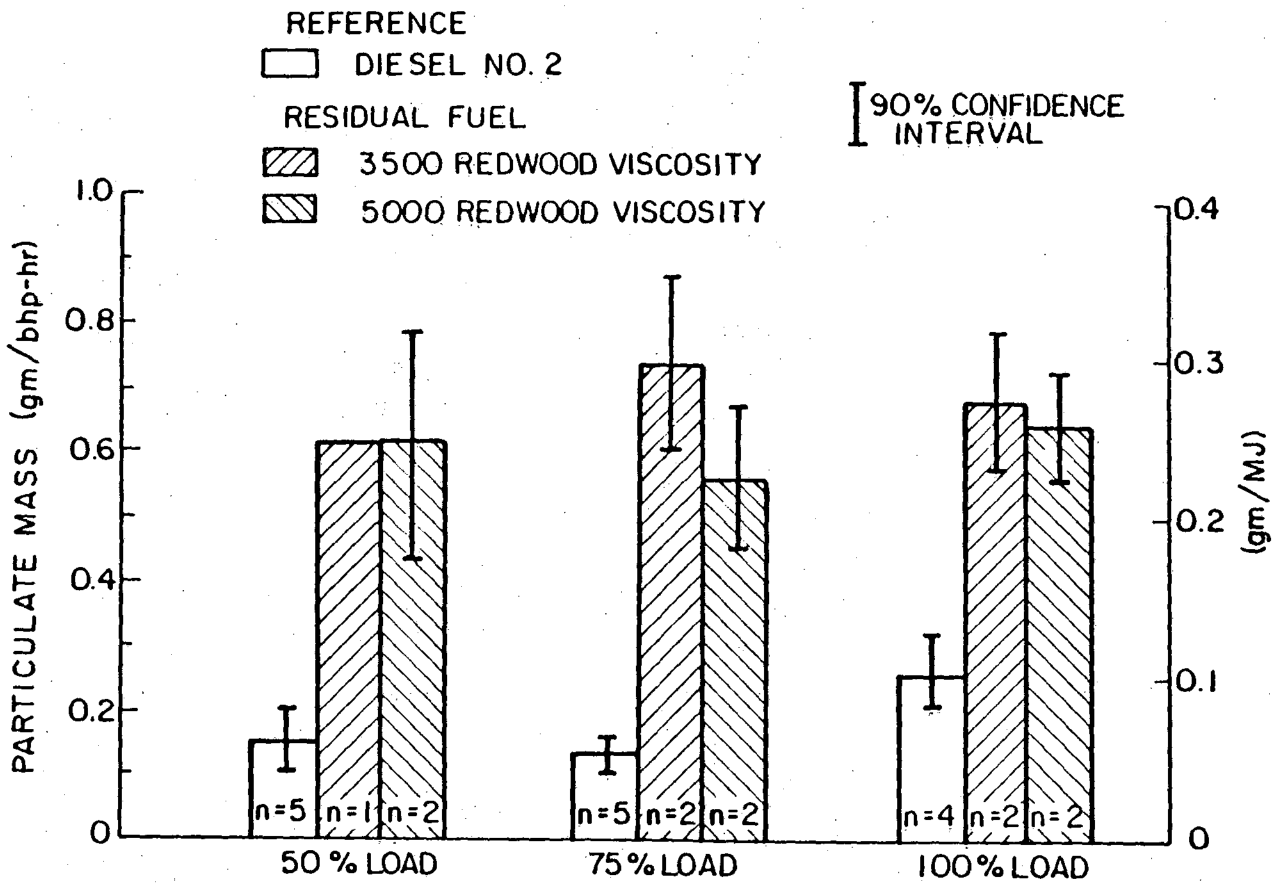

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Figure 2. Specific Particulate Emission (gm/bhp-hr) for three fuels at varying load setting for no water addition; n = number of samples.

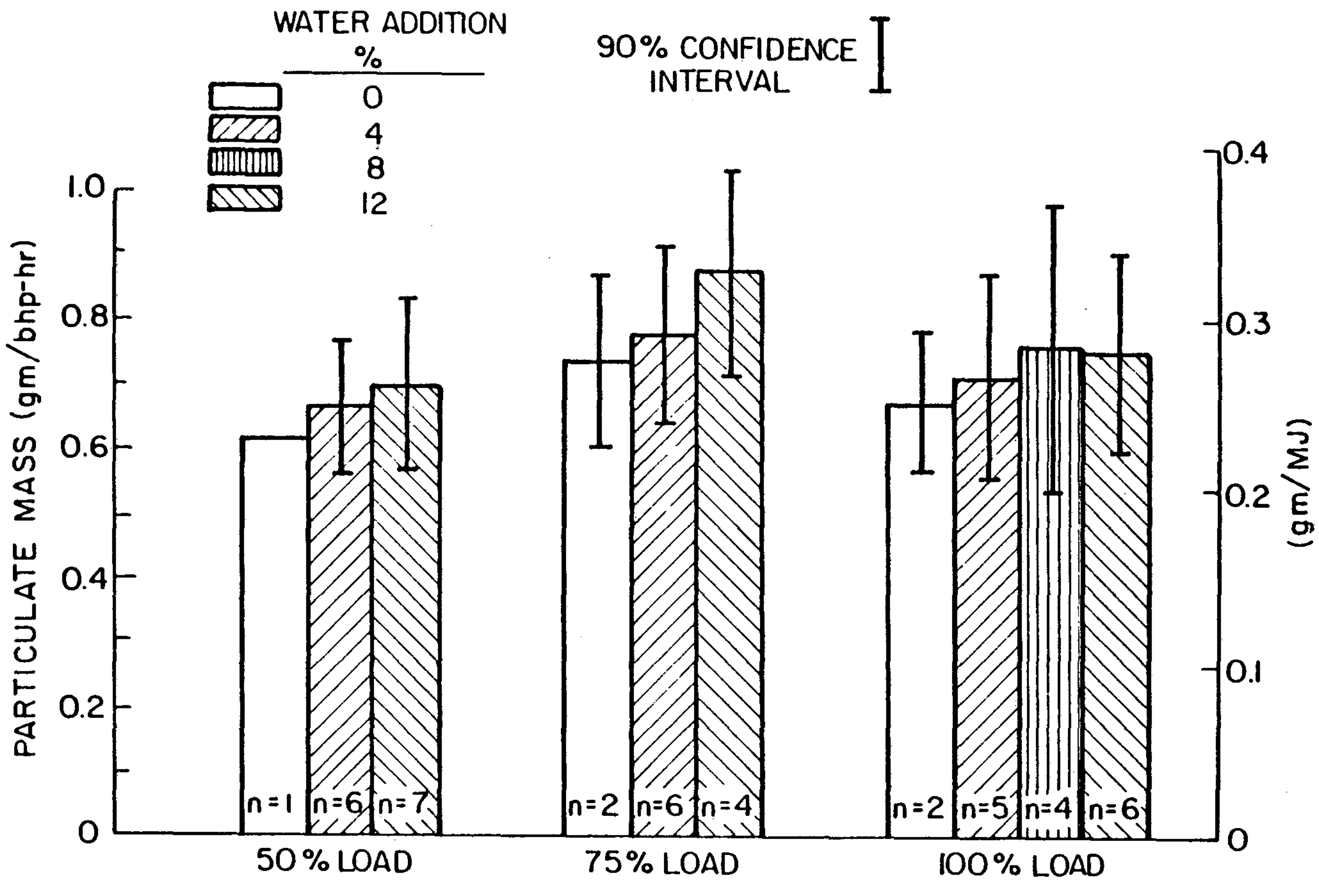

Figure 3. Specific Particulate Emission (gm/bhp-hr) at three load settings for varying levels of water addition (mean values averaged over all water droplet diameters); 3500 Redwood viscosity fuel, n = number of samples.

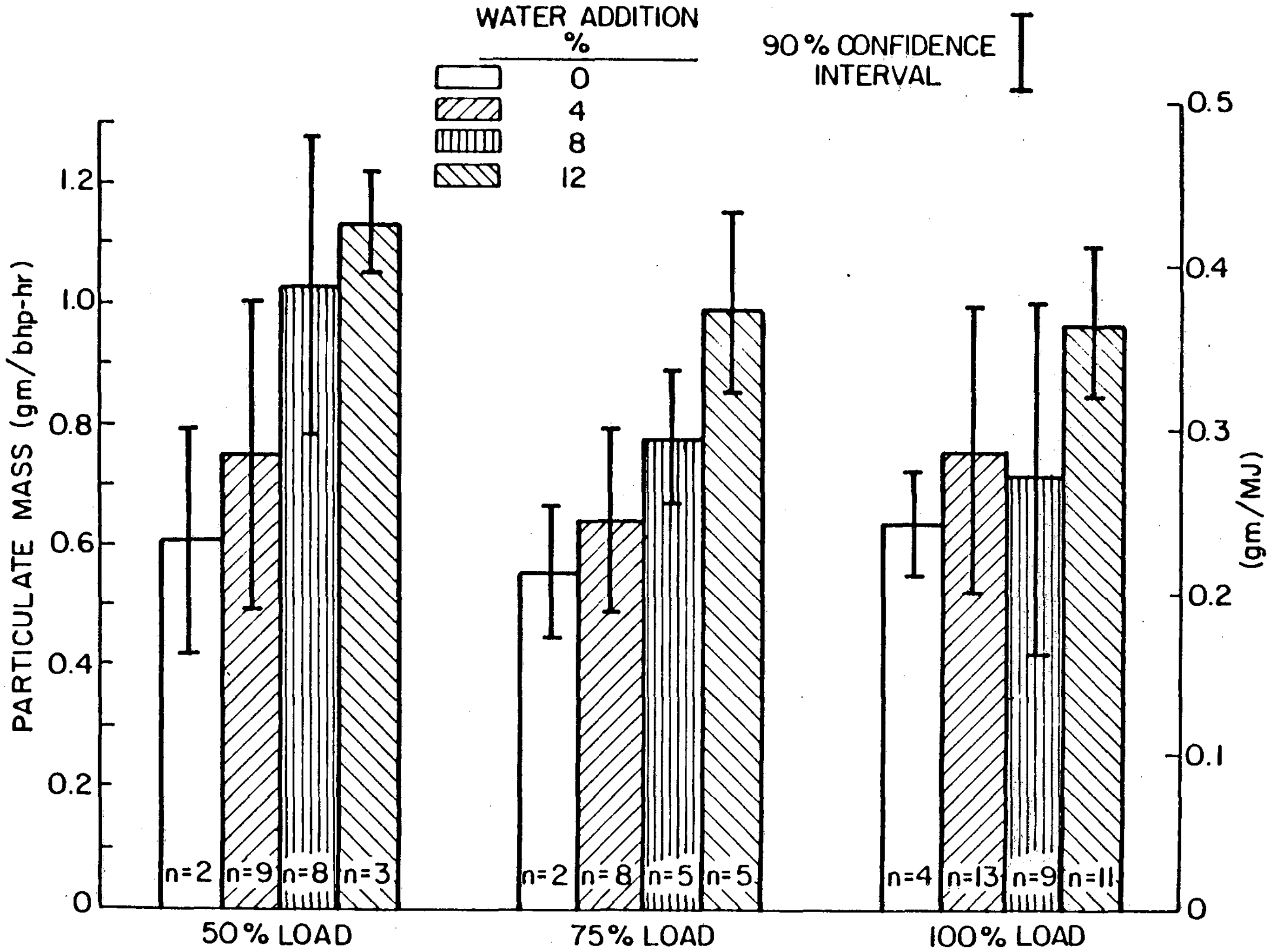

Figure 4. Specific Particulate Emission (gm/bhp-hr) at three load settings for varying levels of water addition (mean values averaged over all water droplet diameters); 5000 Redwood viscosity fuel, n = number of samples.

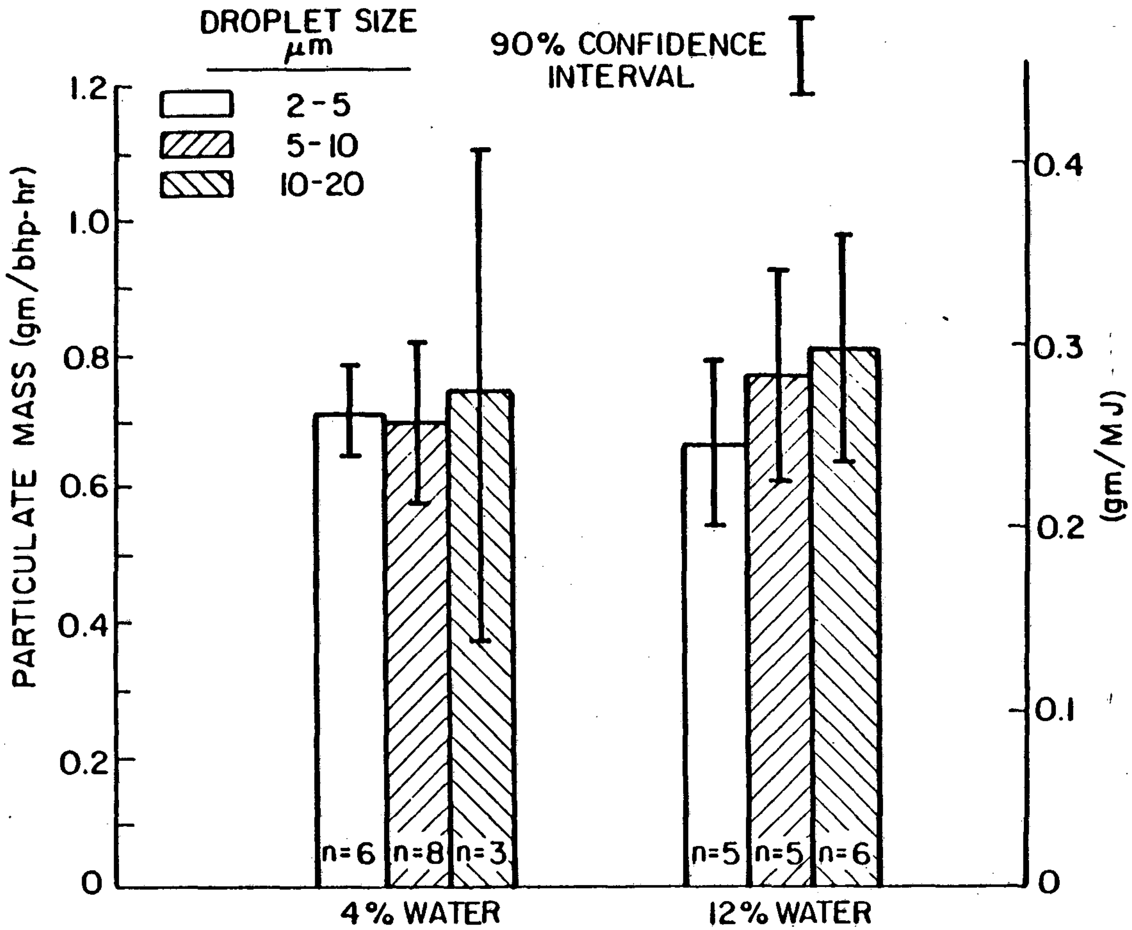

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Figure 5. Specific Particulate Emission (gm/bhp-hr) at two levels of water addition with varying water droplet diameter in 3500 Redwood viscosity fuel; n = number of samples and the mean value is averaged over 50%, 75%, and 100% load settings.

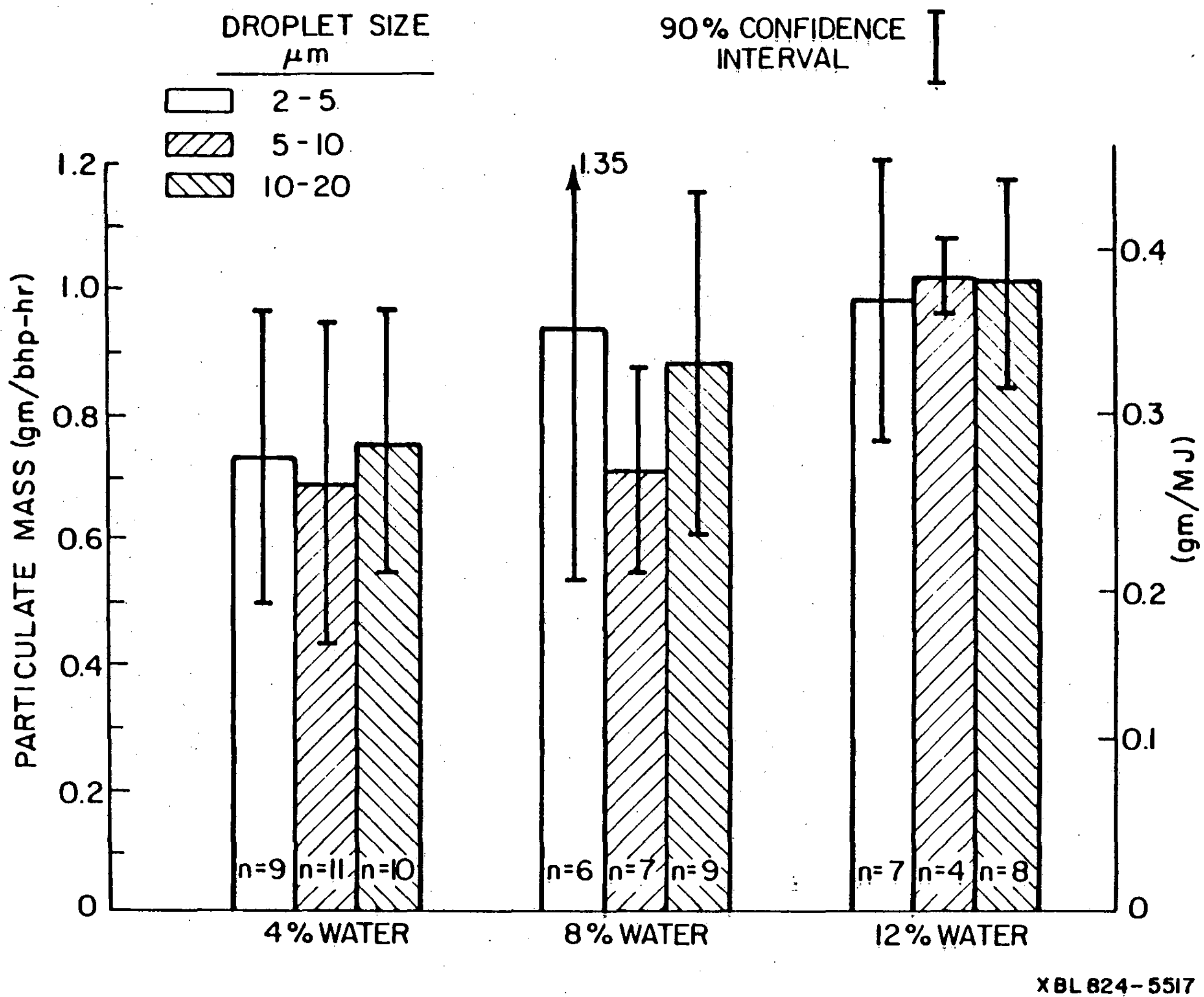

Figure 6. Specific Particulate Emission (gm/bhp-hr) at three levels of water addition with varying water droplet diameter in 5000 Redwood viscosity fuel; n = number of samples and the mean value is averaged over 50%, 75%, and 100% load settings.

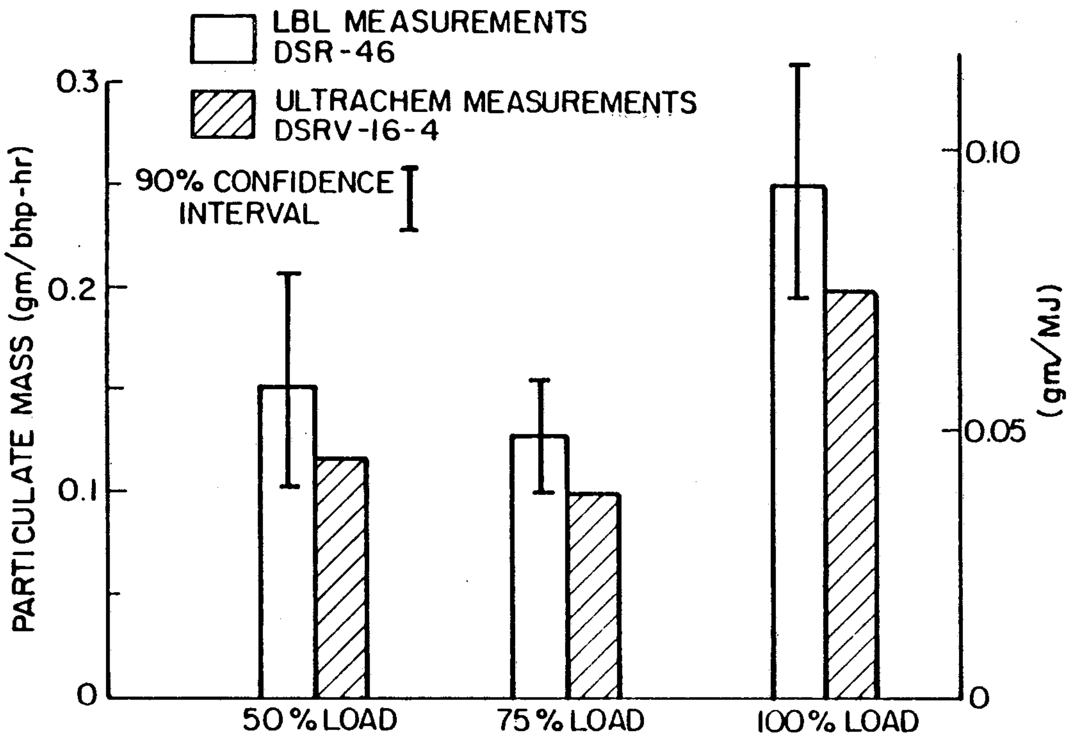

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Figure 7. Specific Particulate Emission (gm/bhp-hr)--Comparison of LBL and Ultrachem Measurements with diesel No. 2 fuel.

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