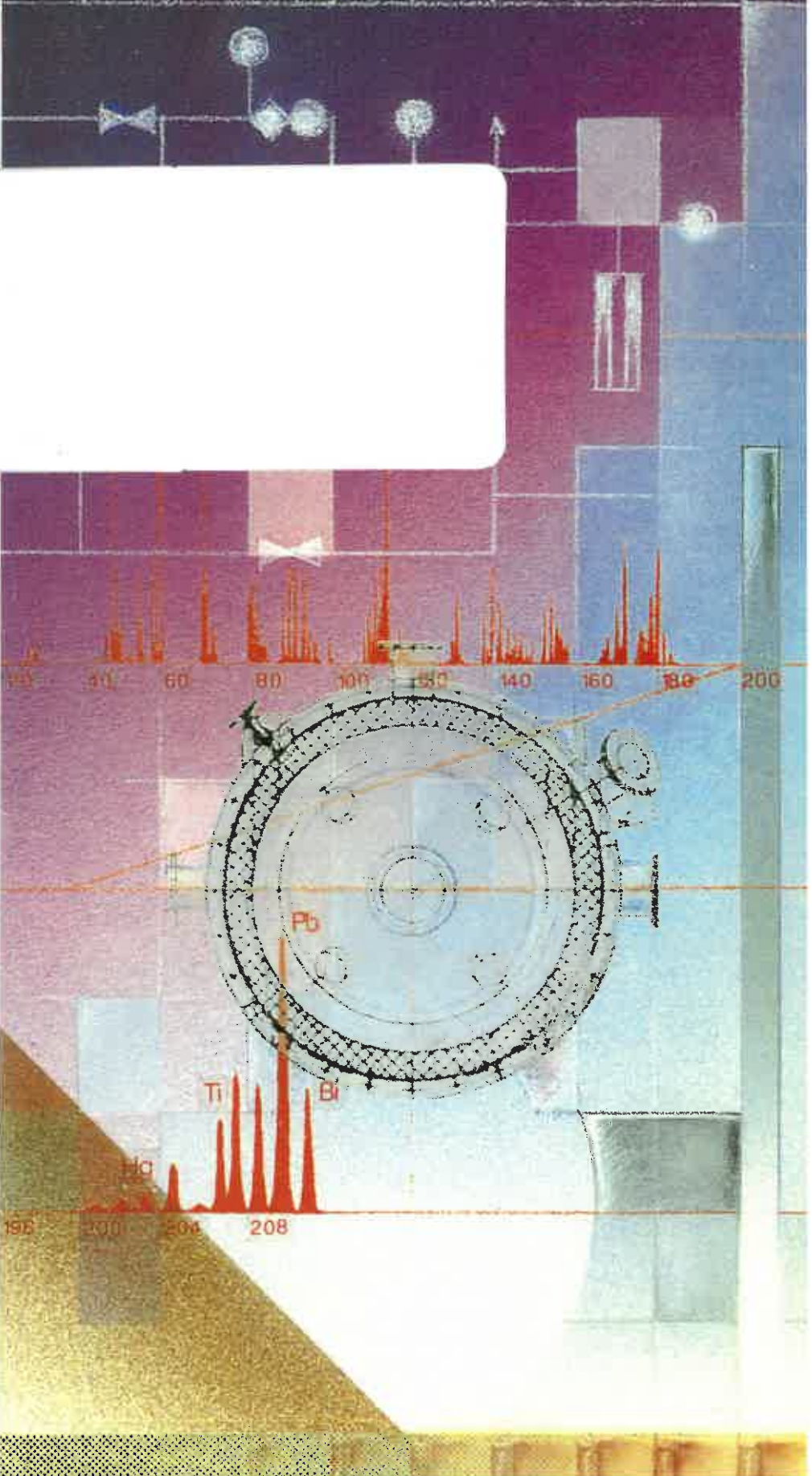




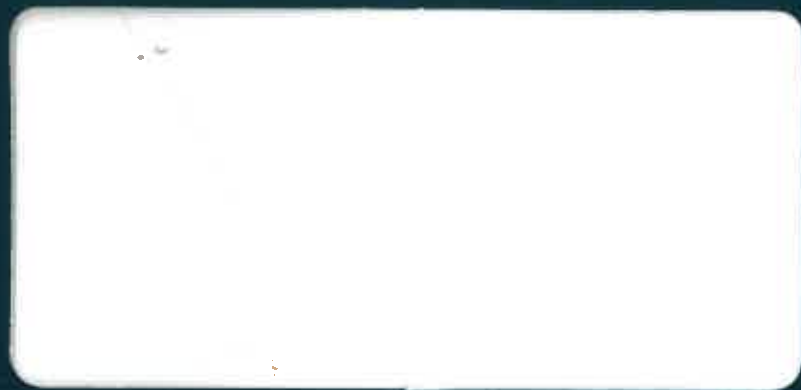
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INVESTIGATION REPORT CET/IR56R

**SULPHUR & PARTICULATE EMISSIONS
FROM A DIESEL LOCOMOTIVE**

by

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Report to Freight Corp.

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SUMMARY.

The influence of diesel fuel extenders on exhaust pollution emissions from an 81 class locomotive was evaluated at the Enfield testing facility. The locomotive was subject to a multi-mode test cycle consisting of 20 minutes operation in notch positions idle, 2, 4, 6 and 8.

A portion of the exhaust gases were ducted to ground level, from which an aliquot was taken for the determination of gas (carbon monoxide, CO, carbon dioxide, CO₂ and sulphur dioxide, SO₂) and particle concentrations (total, less than 10 µm and less than 2.5µm) at each mode of the test cycle.

The report presents details of the exhaust gas composition in terms of its volumetric composition (ppm). Details for the conversion of volumetric concentrations to fuel specific units are supplied.

No significant variation in volumetric emission rates was found between the five tests within the accuracy of the measurements. Comparisons with previous tests on the same locomotive by Williams et al., (1996) indicate that the sampling methodology employed in the present tests was considerably more efficient for the analysis of SO₂ and particulate matter.

1 OBJECTIVE.

To determine the emission rates of sulphur dioxide (SO₂), aldehydes and particulate pollutants from Freight Rail locomotive 8154 as a function of engine notch position for a range of fuel qualities.

2 METHODOLOGY.

2.1 Sampling Set-up.

An exhaust sampling duct 100 mm in diameter and 15 m in length, was mounted so that its inlet was immediately above the exhaust stack of the locomotive. The purpose of the duct was twofold: 1) to allow easy access to the exhaust gases at ground level and 2) provide time for particles to agglomerate to sizes more typical of their ambient equilibrium size (circa 0.5 µm).

2.2 Sampling Procedures.

2.2.1 Gaseous Constituents.

An aliquot of the raw exhaust gases were continuously sampled through an electrically heated sampling system connected to the exhaust duct with 1/4 inch stainless steel tubing. The aliquot was subsequently diluted with instrument grade air by a factor of approximately 10. The purpose of the dilution system was threefold: 1) prevent condensation of combustion generated water vapour thereby minimising the scavenging effect of condensation on SO₂ and aldehydes. 2) minimise the effect of high NO_x concentrations on the Sep-Pak[®] aldehyde sampling cartridges. 3) to dilute the raw SO₂ concentration within the dynamic range of the employed sulphur analyser.

The dilution rate was measured by two methods. In the first system the addition of instrument grade air was controlled by a precision needle valve and measured by a rotameter. The addition of raw exhaust was controlled by a precision needle valve and measured periodically with a Buck[®] digital bubble flow meter. The second method involved a comparison of raw CO and CO₂ concentrations with those derived from the dilution system during each notch position.

Concentrations of SO₂ were determined using flame photometry. CO and CO₂ concentrations were measured using a non-dispersive infrared instrument. Aldehydes were collected on Sep-Pak[®] 2,4-dinitrophenylhydrazine (DNPH) coated silica cartridges. Levels of methanal (formaldehyde - HCHO), ethanal (acetaldehyde - CH₃CHO) and 2-propenal (acrolein - CH₂=CHCHO) collected on the Sep-Pak[®] cartridges were determined by High Pressure Liquid Chromatography (HPLC). Some important characteristics of the instruments are listed in Table 1.

Table 1. Typical Instrument Characteristics

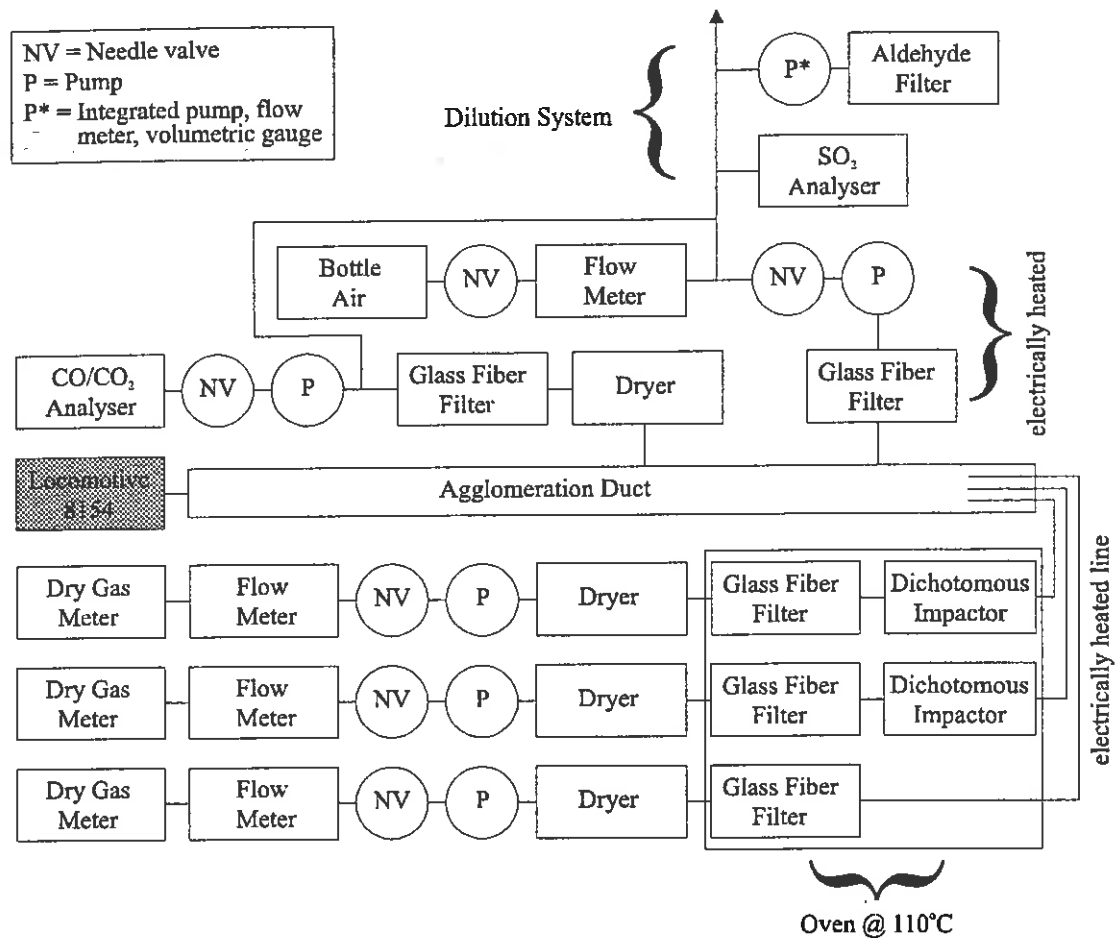
| Instrument | FSD | Accuracy (% FSD) | Response time (s) |
|--------------------|----------------|------------------|-------------------|
| CO | 2000 ppm | 1 | 10 |
| CO ₂ | 25000 ppm | 1 | 10 |
| SO ₂ | 1 ppm | 1 | 20 |
| Sep-Pak® cartridge | 0.35 g/sampler | 0.0175g/sampler | N/A |

2.2.2 Particulate Matter.

Raw exhaust was sampled through 1/4 inch stainless steel tubing connected to the exhaust duct. The tubing was electrically heated to a temperature of approximately 120°C. The tubing transferred exhaust gases into an oven heated to a temperature of 110°C. Three stainless steel filter holders were housed in the oven, two of which were preceded by a dichotomous impactor designed to remove particles greater than 2.5 μm and 10μm respectively. The impactors were made from brass using the design parameters of Marple and Willeke (1976). Particulate matter was collected on 47 mm Whatman GF/A glass fiber filters capable of collecting particulate matter greater than 0.1 μm in size. After particle collection the aliquot's were drawn through ice-cooled condensers and the total volume sampled measured with dry gas meters. Flow rates were controlled with precision needle valves and measured with rotameters. Prior to measurement the filters were pre-treated in an oven at 120°C. The collected samples were heated in an oven to 120°C and weighed with an analytical balance to an accuracy 0.1 mg.

Figure 1 displays a schematic representation of the sampling system employed to monitor the composition of the exhaust gases and particulate concentrations.

Figure 1: Schematic of Sampling System.



2.3 Test Procedure.

A multi-mode test procedure involving notch settings idle, 2, 4, 6 and 8 was used for evaluating fuel consumption and pollutant emissions. Sampling time for each notch position was approximately 20 minutes.

During each notch setting SO₂, CO, CO₂ and particulate matter were continuously sampled. Data obtained from the SO₂ and CO/CO₂ analysers were digitally recorded every second and manually recorded in approximately three minute intervals. Volumetric measurements for the particulate samples were manually recorded from the dry gas meter gauges.

Dilution rates during each notch setting were determined by comparing the CO and CO₂ concentrations between the diluted and raw sampling systems (Figure 1). Periodically the flow rates of the heated pump and dilution air were also measured. This typically occurred at the end of every second notch setting while replacing filters within the gaseous sampling system.

The volume of diluted exhaust sampled through the Sep-Pak[®] cartridges was manually recorded from the digital output of the fully integrated pump employed. This pump incorporated a flow meter, flow control mechanism and digital volumetric gauge.

SO₂ was calibrated with 50 ppm SO₂ in nitrogen at the beginning and end of the test procedure. Instrument signal amplification was tested at 1 %, 10 % and 100 % at the beginning and end of each experiment.

3 RESULTS AND DISCUSSION.

3.1 Formation of results.

Volumetric concentrations (ppm) of CO, CO₂ and SO₂ were measured in notch positions idle, 2, 4, 6 and 8 for five tests. Particulate matter was measured likewise in terms of a mass per unit volume (g/m³). Mass per volume particulate concentrations were converted to volumetric concentrations assuming that the particles consisted purely of carbon. The diluted measurements were multiplied by the dilution factor to give the value for pure exhaust. The measured CO/CO₂ ratios were used purely for extracting the dilution rate and are not presented here as the exhaust concentration of these species were measured concurrently by the Department of Mineral Resources.

The volumetric concentrations given in Tables 2-9 can be converted to a fuel specific emission rate using a carbon mass balance technique. In previous studies of diesel locomotive emissions (Lilley, 1996 and Williams et al., 1996), volume fractions were converted to a fuel specific mass emission rate assuming that the molecular weight of diesel fuel corresponded to an elemental composition of CH_{1.85} (AS 2077, 1982). For example, consider a steady state emission profile consisting of the following constituents: 60000 ppm CO₂, 80 ppm CO, 20 ppm HC and 50 ppm PM. The total fuel carbon (TFC) is the summation of all four constituents given and is equal to 60150 ppm. Now to obtain a fuel specific emission rate of PM, for example, the following formulation would be employed:

$$\begin{aligned} \frac{\text{PM}}{\text{Fuel}} \left(\frac{\text{kg}}{\text{kg}} \right) &= \left[\frac{\text{PM}(\text{ppm})}{\text{TFC}(\text{ppm})} \right] \times \left[\frac{\text{PM}(\text{mw})}{\text{TFC}(\text{mw})} \right] \\ &= \left[\frac{50}{60150} \right] \times \left[\frac{12.01}{13.85} \right] \\ &= 7.21 \times 10^{-4} \text{ or } 0.721 (\text{g/kg}) \end{aligned}$$

where: mw = molecular weight
mw of CH_{1.85} = 13.85

3.2 Particulate Matter.

Volumetric concentrations (ppm) of total particulate matter, particulate matter less than 10 μm and particulate matter less than 2.5 μm , for tests 1-5 are given in Tables 2-4 and Figures 2-4.

Table 2 and Figure 2 display values of total particulate concentration. Given the average error associated with the particulate measurements is approximately 7.5 %, the values for all fuel blends are similar in magnitude in corresponding notch positions. The only exception are the values obtained in notch 4 of test 1, which was higher for all three particulate class sizes and may incorporate errors associated with the initial set-up. The volumetric concentrations of particulate matter less than 10 μm in diameter is given in Table 3 and Figure 3. Again the magnitude of emissions in a given notch position is observed to be similar for all fuel types tested. Emission rates for particles less than 2.5 μm (Table 4, Figure 4) are also observed to be similar for all 5 tests in corresponding notch positions. For all three particle class sizes the volumetric emission rates were observed to increase with notch position.

The average volumetric concentration for total particulates measured in this study is 53 ppm. An average value of 37 ppm was obtained from the same locomotive for the same notch positions using standard fuels by Williams et al., (1996). The values obtained for the previous test were therefore on average 70 % of those obtained in the present test. Lilley (1996) notes that average fuel specific values obtained for the previous tests were approximately 75 % of those obtained by Fritz (1994) for an EMD 12-710G3A engine with a fuel sulphur content of 0.02 %. The values were also found to be 50 % and 77 % of those obtained by Fritz and Cataldi (1991) from an EMD 12-645E3B engine operating with a fuel sulphur content of 0.33 % and 0.01 % respectively. The revised system employed for present tests therefore appears to be a more accurate system than that used in the previous study.

Table 5 and Figure 5 present the percentage of particulate matter less than 10 μm . The greatest proportion of coarse material was found for idle. Values for notch positions 2, 4, 6 and 8 were found to be similar in magnitude. The percentage of particulate matter less than 2.5 μm (Table 6, Figure 6) was also found to be lowest in idle and similar for notch positions 2, 4, 6 and 8. Average values of particulate matter less than 10 μm and 2.5 μm was 75 % and 57 % respectively. Previous work by Williams et al., (1996) found the percentage of particulate matter less than 2.5 μm to be 77 % for corresponding notch positions for tests performed with standard diesel fuel. Measurements were not made for particles less than 10 μm . The lower average value of particles less than 2.5 μm obtained for the present tests are primarily due to low idle ratios which were not observed in the previous study. The greater proportion of coarser particles obtained in the present study may also be due to increased sampling efficiency. Coarser particle concentration in the previous work by Williams et al., (1996) may have been lower due to sample loss in the condensation collection system of test 1 and increased loss of volatile matter from temperature extremes in the agglomeration duct in test 2.

3.3 Sulphur Dioxide (SO₂).

Table 7 and Figure 7 present volumetric concentrations of SO₂ measured for all five tests. Some problems were experienced with the sampling system leading to lower number of reported values compared with the particulate measurements. Volumetric concentrations of SO₂ were observed to increase with notch position. The magnitude for all five tests was found to be similar in comparable notch positions. Table 8 presents average values of SO₂ found in the present study, values calculated from the complete oxidation of 0.2 % fuel sulphur content and those obtained in the previous study by Williams et al., (1996). The sampling methodology employed in the present study which minimised the effects of condensation and temperature was more appropriate than that previously used by Williams et al., (1996) in which considerable loss of SO₂ occurred during the removal of combustion generated water. Average values for the present study are similar to those expected from complete oxidation of fuel sulphur to SO₂ for notch positions idle and 2. Average values for the higher notch positions however, were somewhat lower than those calculated on the assumption of complete fuel sulphur oxidation.

3.4 Aldehydes.

4 CONCLUSIONS.

There was little difference in any of the volumetric pollutant emission rates between any of the fuels tested. In this study the bulk of the particulate matter was found to have an aerodynamic diameter less than 10 µm. Some differences were observed in the percentage of particulate matter less than 2.5 µm in diameter between the present study and previous study by Williams et al., (1996) for the same locomotive. The sampling methodology employed for the present study was found to be more efficient for the measurement of particulate matter and SO₂ than that used in the previous study.

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Table 2. Concentration (ppm) of Total Particulate Matter.

| Notch | Test 1 | Test 2 | Test 3 | Test 4 | Test 5 |
|-------|--------|--------|--------|--------|--------|
| Idle | N/A | 41 | 39 | 18 | 18 |
| 2 | N/A | 30 | 29 | 28 | 30 |
| 4 | 91 | 62 | 50 | 50 | 59 |
| 6 | 69 | 62 | 59 | 51 | 58 |
| 8 | 76 | 67 | 62 | 51 | 72 |

* N/A = not measured

Table 3. Concentration (ppm) of Particulate Matter Less Than 10 μm .

| Notch | Test 1 | Test 2 | Test 3 | Test 4 | Test 5 |
|-------|--------|--------|--------|--------|--------|
| Idle | 7 | 8 | 7 | 5 | 8 |
| 2 | N/A | 23 | 26 | 24 | 26 |
| 4 | 77 | 45 | 45 | 45 | 48 |
| 6 | 59 | 51 | 53 | 48 | 48 |
| 8 | 61 | 50 | 52 | 51 | 56 |

Table 4. Concentration (ppm) of Particulate Matter Less Than 2.5 μm .

| Notch | Test 1 | Test 2 | Test 3 | Test 4 | Test 5 |
|-------|--------|--------|--------|--------|--------|
| Idle | 7 | 5 | 6 | 5 | 6 |
| 2 | N/A | 19 | 22 | 20 | 22 |
| 4 | 48 | 33 | 38 | 35 | 39 |
| 6 | 32 | 44 | 43 | 36 | 35 |
| 8 | 42 | 43 | 42 | 34 | 41 |

Table 5. Ratio of Particulate Matter Less Than 10 μm (%).

| Notch | Test 1 | Test 2 | Test 3 | Test 4 | Test 5 |
|---------|--------|--------|--------|--------|--------|
| Idle | N/A | 19 | 19 | 27 | 44 |
| 2 | N/A | 76 | 91 | 86 | 85 |
| 4 | 85 | 72 | 90 | 91 | 82 |
| 6 | 85 | 82 | 90 | 93 | 83 |
| 8 | 80 | 75 | 84 | 100 | 77 |
| Average | 83 | 65 | 75 | 79 | 74 |

Table 6. Ratio of Particulate Matter Less Than 2.5 μm (%).

| Notch | Test 1 | Test 2 | Test 3 | Test 4 | Test 5 |
|---------|--------|--------|--------|--------|--------|
| Idle | N/A | 13 | 15 | 28 | 34 |
| 2 | N/A | 64 | 76 | 70 | 73 |
| 4 | 52 | 54 | 77 | 69 | 67 |
| 6 | 46 | 72 | 73 | 70 | 60 |
| 8 | 55 | 64 | 68 | 67 | 57 |
| Average | 51 | 53 | 62 | 61 | 58 |

Table 7. Concentration (ppm) of Sulphur Dioxide (SO_2).

| Notch | Test 1 | Test 2 | Test 3 | Test 4 | Test 5 |
|-------|--------|--------|--------|--------|--------|
| Idle | 3 | 3 | 2 | 3 | 2 |
| 2 | 4 | 5 | 4 | 5 | 5 |
| 4 | N/A | N/A | 6 | 6 | 6 |
| 6 | N/A | 7 | 6 | N/A | 6 |
| 8 | N/A | 8 | 6 | N/A | 6 |

Table 8. Average concentration (ppm) of Sulphur Dioxide (SO_2).

| Notch | Present Study | Calculated (0.2 % S) | Williams et al (1996) |
|-------|---------------|----------------------|-----------------------|
| Idle | 3 | 2 | 0.35 |
| 2 | 5 | 6 | 0.42 |
| 4 | 6 | 8 | 0.46 |
| 6 | 6 | 10 | 0.49 |
| 8 | 7 | 11 | 0.50 |

PMtotal vs Notch Position

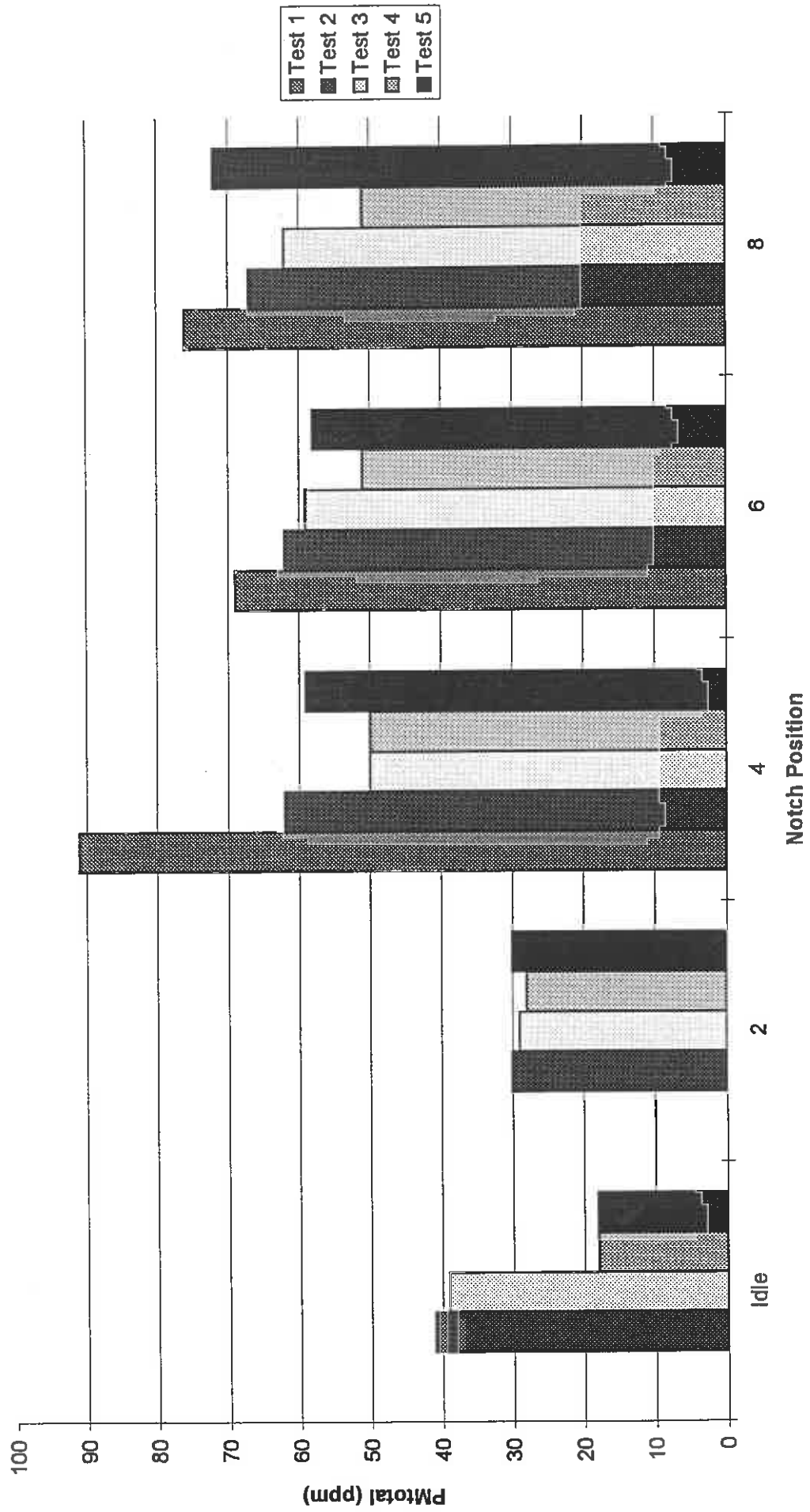


Figure 2. Concentration (ppm) of Total Particulate Matter.

PM10 vs Notch Position

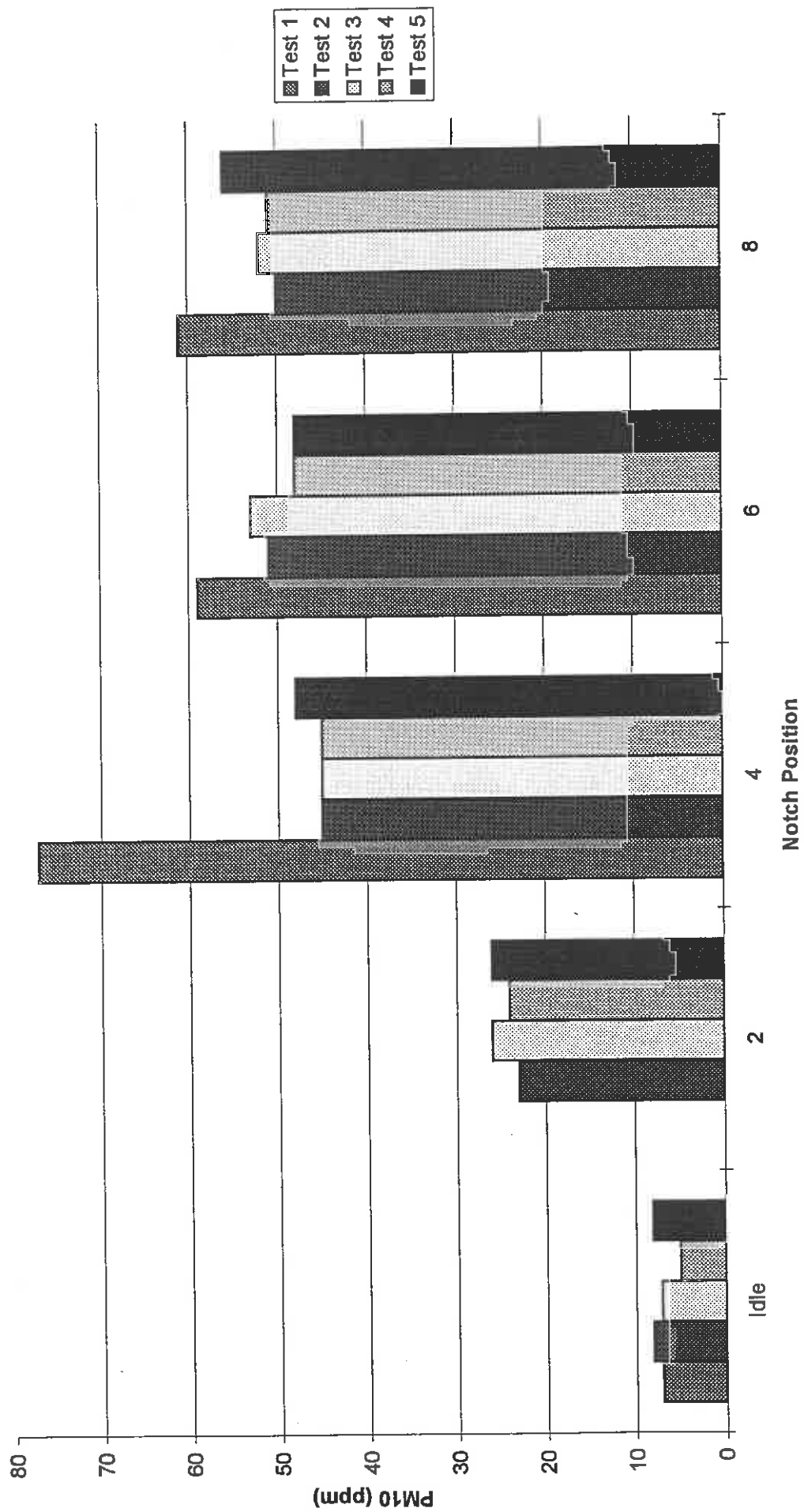


Figure 3. Concentration of Particulate Matter Less Than 10 μm.

PM2.5 vs Notch Position

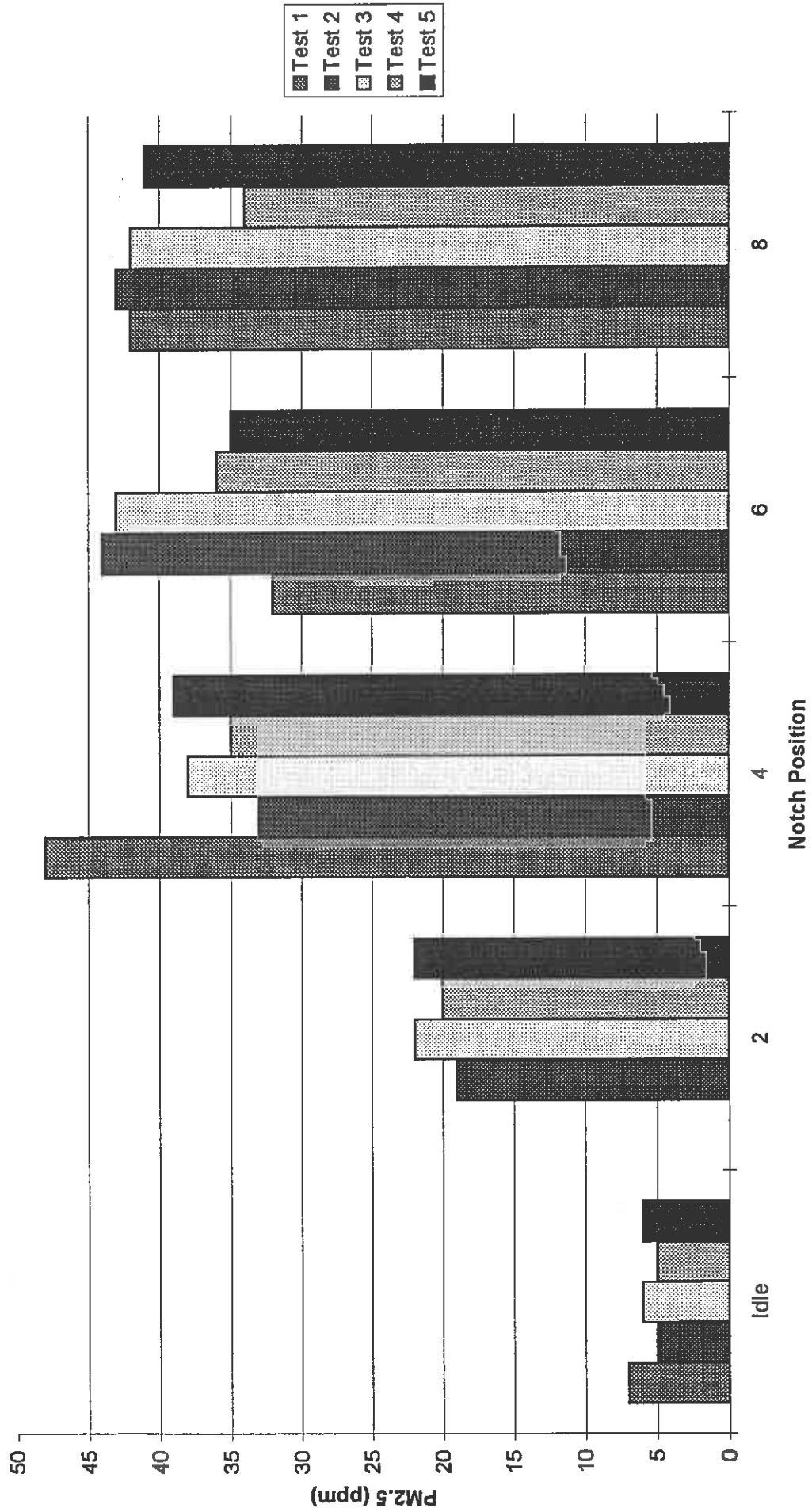


Figure 4. Concentration (ppm) of Particulate Matter Less Than 2.5 μm .

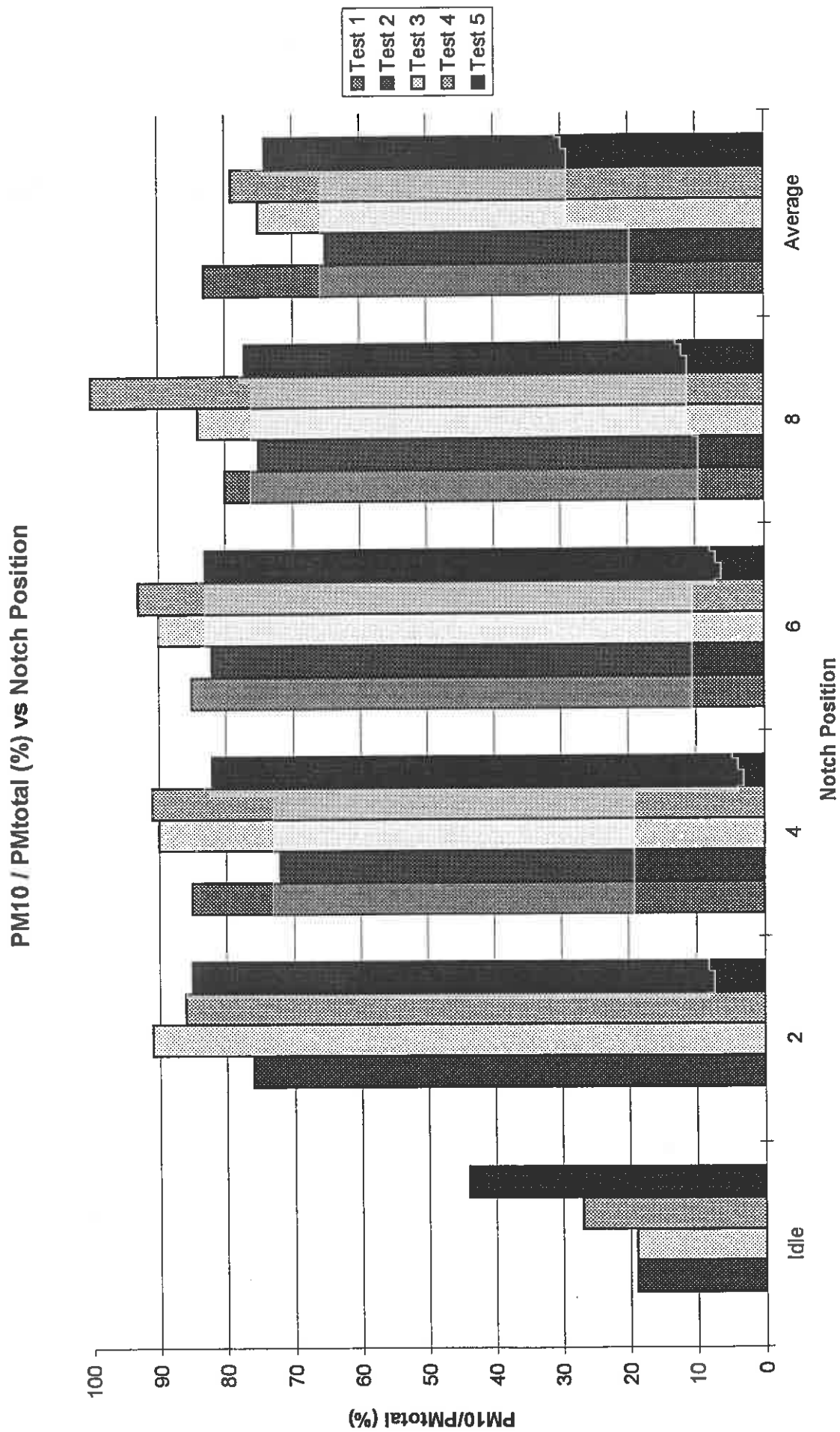


Figure 5. Ratio of Particulate Matter Less Than 10 μm .

PM2.5 / PMtotal (%) vs Notch Position

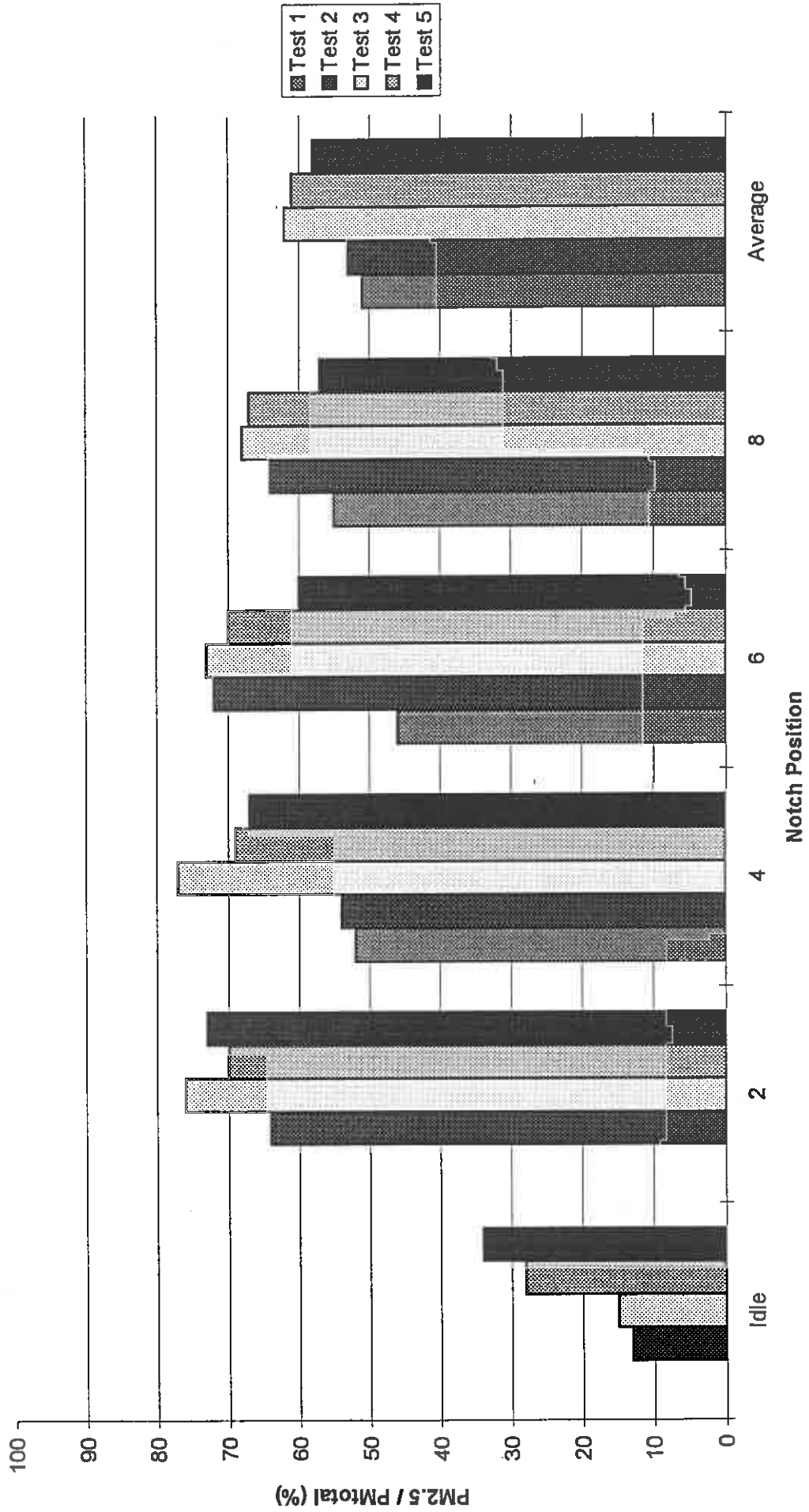


Figure 6. Ratio of Particulate Matter Less Than 2.5 μm.

SO2 vs Notch Position

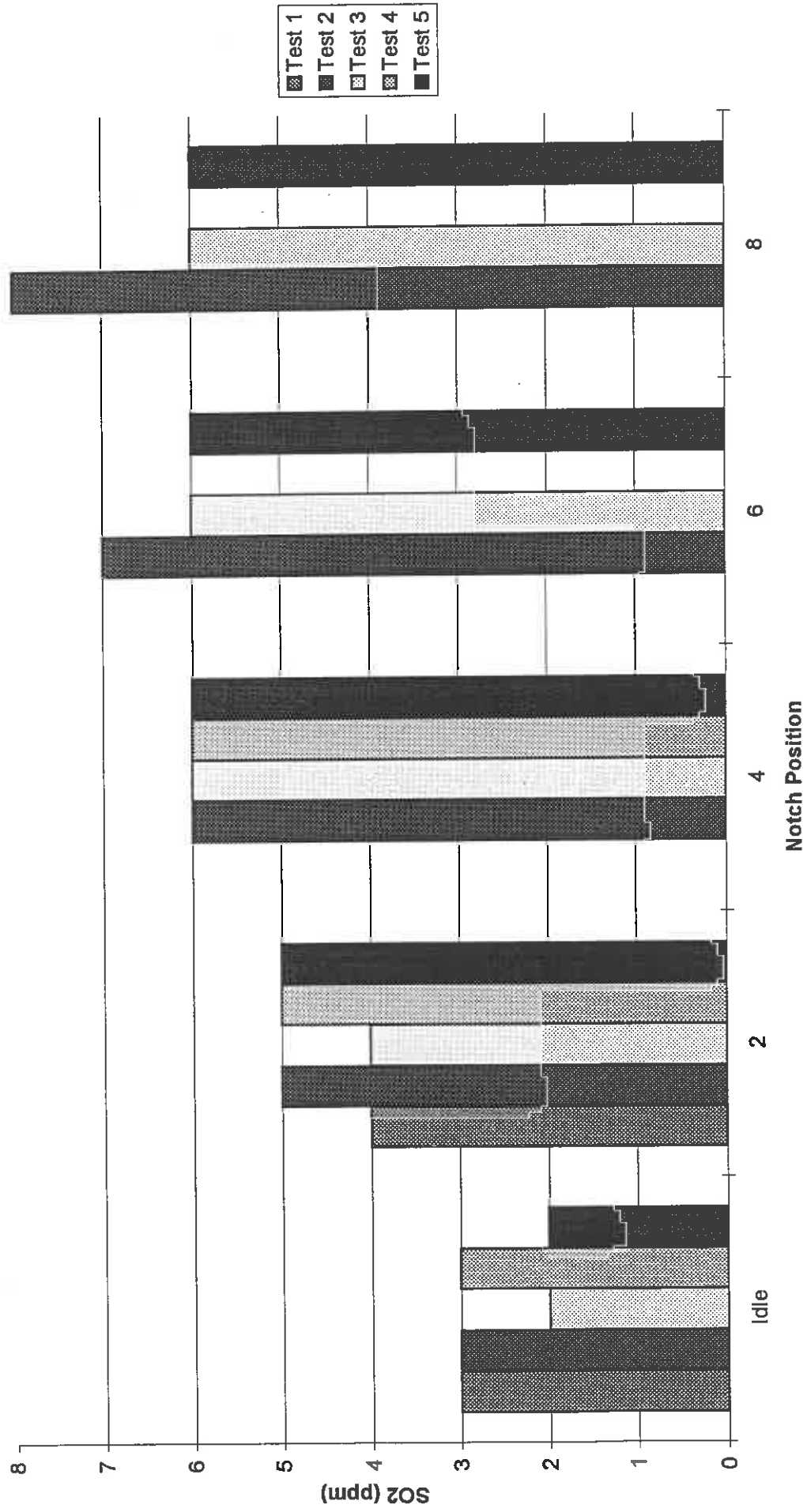


Figure 7. Concentration (ppm) of Sulphur Dioxide (SO₂).