AD A

# EMISSIONS FROM A 6.5L HMMWV ENGINE ON LOW SULFUR DIESEL FUEL AND JP-8

**INTERIM REPORT**
**TFLRF No. 376**


by
**Edwin A. Frame**
**Matthew G. Blanks**

**U.S. Army TARDEC Fuels and Lubricants Research Facility**
**(SwRI®) Southwest Research Institute®**
**San Antonio, TX**


**For**
**U.S. Army Corps of Engineers**
**Construction Engineering & Research Laboratory**
**Champaign, IL**

Under Contract to
**U.S. Army TARDEC**
**Petroleum and Water Business Area**
**Warren, MI**


Contract No. DAAE-07-99-C-L053 (WD11)




**December 2004**

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**Approved by:**

**Edwin C. Owens, Director**
**U.S. Army TARDEC Fuels and Lubricants**
**Research Facility (SwRI)**

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This project investigated the exhaust emissions produced at various operating conditions by the 6.5L diesel engine that is used to power the Army's HMMWV. Compared to reference diesel fuel, the use of JP-8 fuel resulted in lower levels of NOx and particulate matter. Polycyclic aromatic hydrocarbons (PAH's) were also determined. The JP-8 produced lower levels of exhaust PAH's than the low sulfur certification diesel fuel (LSCD) for most but not all PAH type

14. SUBJECT TERMS

| | | | | | |
|---|---|---|---|---|---|
| Exhaust Emissions | Tactical Vehicle | Diesel Fuel | JP-8 | Particulate matter (PM) | NOx |
| HMMWV | PAH | 6.5L Engine | PAH | ISO 8178 | |
| EPA Off-road transient test cycle | | | | | |

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# EXECUTIVE SUMMARY

Emissions from tactical vehicle engines contribute to local and regional particulate matter (PM) air pollution. Emissions from these sources are not well understood, and the U.S. Army requires methods/models to predict PM10 and PM2.5 emissions from these military-unique sources. To develop these methods/models, the mass and chemical speciation of tactical vehicle engine emissions need to be characterized. This project investigated the exhaust emissions produced at various operating conditions by the 6.5L diesel engine that is used to power the Army's HMMWV. Compared to reference diesel fuel, the use of JP-8 fuel resulted in lower levels of NOx and particulate matter.

## FOREWARD/ACKNOWLEDGMENTS

The U.S. Army TARDEC Fuels and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, performed this work during the period February 2003 through December 2004 under Contract No. DAAE-07-99-C-L053. The work was funded by the U.S. Army Corps of Engineers, Construction Engineering Research laboratory (CERL), Champaign, Illinois. The U.S. Army Tank-Automotive RD&E Center, Petroleum and Water Business Area, Warren, Michigan administered the project. Mr. Luis Villahermosa (AMSTA-RBFF) served as the TARDEC contracting officer's technical representative. Mr. Mike Kemme served as the project technical monitor.

Test results presented in this report were generated by the Department of Emissions Research (DER), Automotive Products and Emissions Research of Southwest Research Institute (SwRI), for the U.S. Army TARDEC Fuels and Lubricants Research Facility/SwRI (TFLRF),. This work was conducted under the DER management of Mr. Terry L. Ullman, Mr. John J. Elizondo, Staff Technician, Mr. Juan G. Vega, Technician, and Mr. Rodney E. Grinstead provided primary technical support. The authors wish to acknowledge the administrative and report-processing support provided by Linda De Salme.

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## LIST OF ILLUSTRATIONS

## SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| CFR | Code of Federal Regulations |
| DER | Department of Emissions Research |
| GM | General Motors |
| HMMWV | High-Mobility Multipurpose Wheeled Vehicle |
| hp | Horse Power |
| ISO | International Standards Organization |
| L | Liter |
| LSCD | Low Sulfur Certification Diesel Fuel |
| mm | Millimeter |
| NOx | Oxides of Nitrogen |
| PAH | Polycyclic Aromatic Hydrocarbon |
| PM | Particulate Matter |
| RPM | Revolutions per Minute |
| SwRI | Southwest Research Institute |
| TARDEC | U.S. Army Tank-automotive RD & E Center |
| TFLRF | U.S. Army TARDEC Fuels and Lubricants Research Facility |

## 1.0 INTRODUCTION and OBJECTIVE

Exhaust emissions from tactical vehicle engines contribute to local and regional air pollution. The emissions from these sources are not well understood and the Army requires methods/models to predict pollutant emissions from these military unique sources. To develop estimation methods/models, the mass and chemical speciation of tactical vehicle engine emissions need to be characterized. The characterization of these exhaust emissions may also be useful in a method to determine the Army's contribution to atmospheric pollution concentrations at receptor sites of concern.

The objective of the proposed work was development of air pollutant emission factors for military off-road sources that are accepted by regulators. Exhaust emissions from a tactical vehicle engine were determined.

In the Army's tactical/combat vehicle fleet, the HMMWV has both the largest population and accumulates the most operation time. It is powered by a 4-stroke cycle, indirect injection (IDI) diesel engine. IDI engines are known to produce higher levels of soot and particulate matter than direct injected 4-stroke cycle diesel engines of the same size. For these reasons, the HMMWV was selected by ERDC/CERL for the initial determination of exhaust emission factors. In this project, exhaust emissions were collected from a 2002 model year 6.5L GM heavy-duty diesel engine that is typical of those used in the HMMWV.

## 2.0 PROCEDURE

A new 2002 GM 6.5 liter, heavy-duty diesel engine (SN 2722) was used. Engine specifications are given in Table A-1 of Appendix A. The test plan used for accumulating emissions data from the engine is given in Table 1. The engine was initially operated on ASTM No. 2-D diesel fuel for a 100-hour "break-in" procedure. Then, JP-8 (AL-26936) and low sulfur certification diesel (LSCD, EM-4816-F) were used in triplicate 11-mode steady-state tests for measurement of regulated emissions. In addition, JP-8 was used in triplicate nonroad cycle testing over the San Antonio Transient (SAT) cycle for measurement of regulated emissions.

## 2.1 Installation and "Break-In"

The engine was installed in transient capable Test Cell No. 3 as shown in Figure 1. The installation included exhaust "Y" pipe fabrication, engine mount fabrication, and engine accessory belt routing.

ASTM No. 2-D diesel fuel, EM-4747-F, was used for the 100-hour "break-in" procedure. This procedure is outlined in Table B-1 of Appendix B. While setting intake and exhaust restrictions DER encountered dynamometer failure. This failure was believed to be associated with the high speed necessary to reach high idle (3,900 rpm) of the 6.5L engine. The dynamometer was repaired and arrangements were made with TFLRF to limit the engine speed to 3,400 rpm for the duration of the project.

The initial 1.5-hour portion of the break-in was run using factory fill oil contained in the engine, as received. After the initial 1.5-hour portion, the engine oil was changed at 25, 50, and 75 hours using U.S. Army MIL-PRF-2104G reference engine oil of viscosity grade SAE 15W40 (AL-26923). Engine oil at the 100-hour point of the "break-in" procedure was retained in the engine for emission testing.

## 2.2 Test Fuels

Two fuels were used in emission testing of the GM 6.5L engine. JP-8 (AL-26936) was used in three 11-mode steady-state tests and three nonroad transient SAT tests. Low sulfur certification diesel (LSCD EM-4816-F) was used in three 11-mode steady-state tests. Properties for the LSCD are listed in Table 2, and for JP-8 in Table 2A.

| Table 1. Test Plan for Accumulating Emissions Data from GM 6.5L Heavy-Duty Diesel Engine | |
|---|---|
| **Step** | **Description** |
| **1** | Perform emission instrument calibrations as required. Calibrate torquemeter and check signal-conditioning systems. Validate CVS gaseous and particulate sampling systems using propane recovery techniques. |
| **2** | Complete installation of 6.5L engine in transient-capable test cell. |
| **3** | Perform 100-hour break-in using 2D durability diesel fuel EM-4747-F (tank 18). Break-in procedure supplied by the TFLRF. Leave oil from last 25 hours of "break-in" in engine for testing. |
| **4** | Perform fuel change procedure to JP-8 fuel AL-26936, supplied by TFLRF. Change fuel filters, purge fuel supply, etcetera. |
| **5** | Operate engine at rated speed and load for approximately ten minutes, then power validate engine. |
| **6** | Conduct ISO 8178 11-mode test three times using JP-8 fuel. Measure HC, CO, $CO_2$, NOx, and PM on each mode. |
| **7** | Perform fuel change procedure to Low Sulfur Certification Diesel; (LSCD. EM-4816-F). Change fuel filters, purge fuel supply, etcetera. |
| **8** | Operate engine at rated speed and load for approximately ten minutes, then power validate engine. |
| **9** | Conduct ISO 8178 11-mode test three times using LSCD. Measure HC, CO, $CO_2$, NOx, and PM on each mode. |
| **10** | Perform fuel change procedure to JP-8 fuel. Change fuel filters, purge fuel supply, etcetera. |
| **11** | Conduct transient full load torque-map from low to high idle. Use these results to create SAT non-road transient command cycle. |
| **12** | Conduct the SAT non-road transient test cycle three times. Measure HC, CO, $CO_2$, NOx, and PM on each cycle using JP-8. |
| **13** | Report data. |

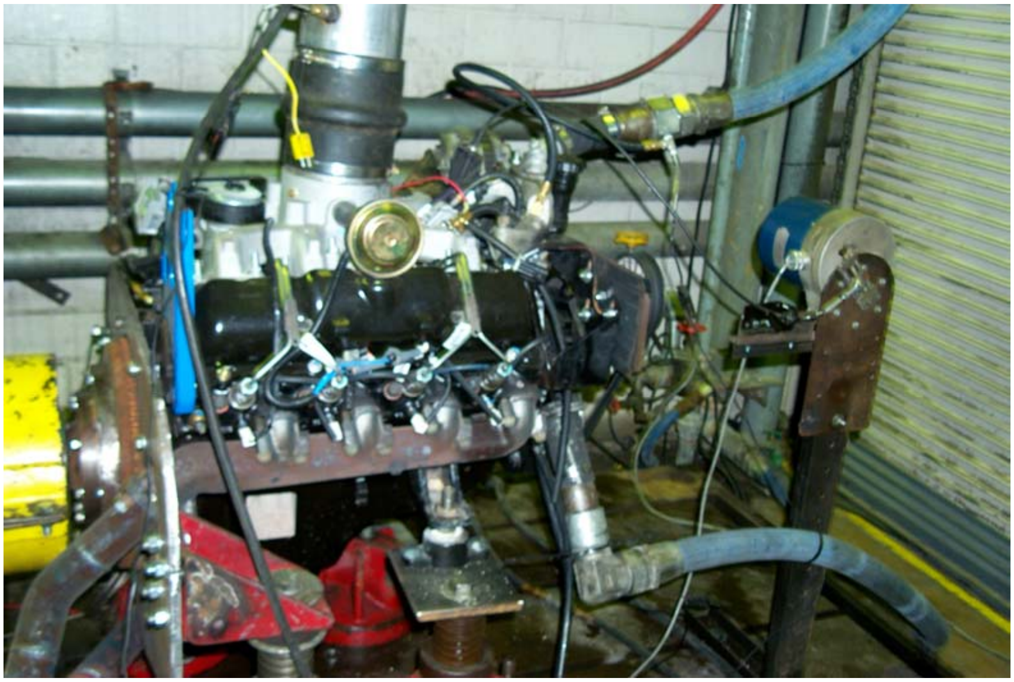


**Figure 1. Installed 2002 GM 6.5L Heavy-Duty Engine**

## 2.3 Emission Testing

After break-in operations, the fuel was changed to JP-8 along with the appropriate fuel filters. The engine was run at 3,400 rpm with full load for ten minutes to purge the 2-D diesel fuel from the system. A power validation sequence was performed at 3,400 rpm. On JP-8, the engine produced 142 hp compared to 153 hp on 2-D diesel fuel. The observed 7.3 percent reduction in power with JP-8 was confirmed to be typical by TFLRF.

Emission instrumentation, torque meter, signal-conditioning systems, and constant volume sampler (CVS) gaseous and particulate sampling systems were checked and calibrated before testing. Eleven modes of the ISO 8178 were performed in triplicate on both JP-8 and LSCD. Testing was also conducted in accordance with EPA Federal Test Procedure (FTP), as specified in the Code of Federal Regulations (CFR), Title 40, Part 89, Subpart E, titled "Control of Emissions from New and In-Use Nonroad Compression-Ignition Engines: Exhaust Emission Test Procedures." Regulated emissions of HC, CO, CO2, NOx and PM were measured using the analyzers and techniques listed in Table 3.

**Table 2. Low Sulfur Certification Diesel Properties**

| FUEL CODE EM-4816-F | | CFR Specification | SwRI Analysis |
|---|---|---|---|
| Item | ASTM | Type 2-D | |
| Cetane Number | D613 | 40-48 | 47.9 |
| Distillation Range: | | | |
| IBP $^{o}C$ | D86 | 171-204 | 189.7 |
| 10% Point, $^{o}C$ | D86 | 204-238 | 223.0 |
| 50% Point, $^{o}C$ | D86 | 243-282 | 259.7 |
| 90% Point, $^{o}C$ | D86 | 293-332 | 309.2 |
| EP, $^{o}C$ | D86 | 321-366 | 358.3 |
| Gravity, API | D287 | 32-37 | 36 |
| Total Sulfur, % | D2622 | 0.03-0.4 | 0.037 |
| Hydrocarbon Composition: | | | |
| Aromatics, % | D1319 | 10[a] | 30.9 |
| Paraffins, Naphthenes, Olefins | D1319 | 90[b] | 69.1 |
| Flashpoint, $^{o}C$ | | 54 (min.) | 62 |
| Viscosity, Centistokes | | 2.0-3.2 | 2.48 |

* Diesel fuel specification as in CFR89 Appendix A, Table 4 for heavy-duty nonroad engines

[a] Minimum

[b] Remainder

| Table 2A. Properties of JP-8, AL-26936 (CL03-0002) | | | | |
|---|---|---|---|---|
| **Test** | **ASTM Method** | **Units** | | **Results** |
| Acidity, Total | D3242 | mg/KOH/g | | 0.011 |
| Aromatics | D1319 | vol. % | aromatic | 16.8 |
| Aromatics | D1319 | vol. % | saturates | 82.2 |
| Olefins | D1319 | vol. % | olefins | 1.0 |
| Distillation | D86 | °C | 10% | 160.0 |
| Distillation | D86 | °C | 20% | 166.2 |
| Distillation | D86 | °C | 50% | 189.6 |
| Distillation | D86 | °C | 90% | 235.1 |
| Distillation | D86 | °C | FBP | 255.9 |
| Distillation | D86 | % | residue | 1.2 |
| Distillation | D86 | % | loss | 0.4 |
| Flash Point | D93 | °C | | 41.39 |
| Density, 15°C, kg/m$^3$ | D4052 | | | 0.7930 |
| Vapor Pressure | D5191 | | | 0.33 |
| Freezing Point | D5972 | | | -48.1 |
| Viscosity @ -20°C | D445 | mm$^2$/s | | 3.48 |
| Net heat of Combustion | D4809 | MJ/kg | | 43.57 |
| Elemental Analysis | D5291 | % | carbon | 85.63 |
| Elemental Analysis | D5291 | % | Hydrogen | 13.15 |
| Sulfur content | D5453 | ppm | | 87.3 |
| Naphthalene's | D1840 | vol % | | 1.62 |
| Copper Strip 2 hr @ 100°C | D130 | | | 1A |
| JFTOT 2.5 h @ 260°C | D3241 | mm Hg | filter pressure drop | 1 |
| JFTOT 2.5 h @ 260°C | D3241 | | tube deposits less than | <2 |
| Existent gum | D381 | mg/100 ml | | 0 |
| Water reactions/Interface rating | D1094 | mL | 1,2 rating | 0 |
| Particulate Matter | D5452 | mg/L | | 0.38 |
| Electrical Conductivity | D2624 | pS/m | | 10 |
| BOCLE | D5001 | mm | | 0.51 |
| SLBOCLE | D6078 | g | | 2150 |
| HFRR | D6079 | µm | | 720 |

A full load torque-map using JP-8 was created at "wide-open-throttle" by increasing the engine's speed from 600 rpm to 3450 rpm at a rate of eight rpm per second. Results of this map, given in Appendix C, were used to generate a San Antonio Transient (SAT) command cycle. Triplicate transient emission tests were conducted according to EPA Federal Test Procedure, as specified in the CFR, Title 40, Part 86, Subpart N with the exception of replacing the EPA "Engine

Dynamometer Schedule for Heavy-Duty Diesel Engines" given in the CFR, Title 40, Appendix I, Subpart F(2) with the proposed San Antonio Transient (SAT) Engine Dynamometer Schedule. Regulated emissions of HC, CO, CO2, NOx and PM were measured for each test using the analyzers and techniques listed in Table 3.

**Table 3. List of Measured Emissions and Analytical Methods**

| Compound | Abbreviation | Analytical Method |
|---|---|---|
| Hydrocarbon | HC | Heated Flame Ionization Detector |
| Carbon Monoxide | CO | Non-Dispersive Infrared Analyzer |
| Carbon Dioxide | CO2 | Non-Dispersive Infrared Analyzer |
| Oxides of Nitrogen | NOx | Chemiluminescent Analyzer |
| Particulate Matter | PM | 90 mm Pallflex Filters |

# 3.0 RESULTS

Modal test work uses percent of full load. Because the full load performance on the LSCD fuel and the JP-8 were different, the loads for the individual modes were different for the two fuels. All the results are given as measured, but to ease comparison between the fuels at equal performance, emissions using LSCD were estimated from the actual data for performance levels equivalent to that obtained on JP-8. Therefore, results for modal test work are given for LSCD and JP-8 as measured and for estimated LSCD for performance equivalent to JP-8.

## 3.1 Regulated Exhaust Emissions

### 3.1.1 Sample of Emission Data Analysis Technique for 11 Steady-State Modes

The three-test average of NOx mass emission rates for the 11 modes are given in Figure 2. In addition, the deviation is also indicated. Detailed results are given in Appendix C. Straight lines were simply used to connect Modes 1 through 5, run at 3,400 rpm; and Modes 6 through 10, run at 2,040 rpm, to highlight the relationships. Figure 3 also gives the NOx mass emission rates for the 11 modes; however, this figure uses a smoothed line to connect the modes to provide a means to better estimate emission levels between modes.

To compare the corresponding modal rate of emission results from each fuel, for each JP-8 power level, a projection from the JP-8 power level to the curve defining the LSCD emission was made. The resulting point was taken to be the NOx level that would be produced by LSCD at the same power achieved on JP-8. Figure 4 shows the estimated LSCD NOx emission points for ease of comparison between the LSCD and JP-8. This estimation technique was used to compare each of the emissions measured for the 11-mode tests on both fuels.

## 3.2 Actual and Estimated Results

### 3.2.1 Steady-State 11 Mode Results

The graphs and tables in this section give the actual and estimated results for the pollutants measured during the 11 mode tests. Results for HC, CO, CO2, NOx, and PM are given in Figures 2 through 14. Results for Soluble organic fraction (SOF) of PM, in terms of percent, are given in Figure 15. Appendix C contains the raw data for all 11-mode tests.

Table 4 lists the emission data for all 11 modes in grams/hour. The brake-specific emissions data are presented in Table 4A. In addition, 8 of the 11 modes were used to compute 8-mode composites using EPA modal weight factors given in the CFR 40, Part 89, for nonroad engine emissions. Composite 8-mode results are also given in Table 4 for JP-8, LSCD and the estimated LSCD points for comparison purposes. The following general trends were observed:

- NOx-JP-8 consistently produced lower levels
- HC- JP-8 consistently produced higher levels
- CO- JP-8 consistently produced higher levels
- PM- Except for idle, JP-8 consistently produced lower levels
- SOF % of PM- In general, JP-8 produced a higher SOF % of PM.

### 3.2.2 Nonroad Transient Cycle (SAT) Results

The SAT cycle was un-normalized using the torque-map data acquired from operating the engine on JP-8 at full-load from idle speed to rated speed. Results from the torque map for JP-8 are given in Figure 11 and Table 5. Results from the three runs of the SAT nonroad transient cycle using JP-8 are summarized in Table 6. Appendix D contains the raw data for these three tests. The average results are plotted in Figure 12. The JP-8 produced slightly lower NOx emissions and substantially lower PM emissions compared to LSCD,

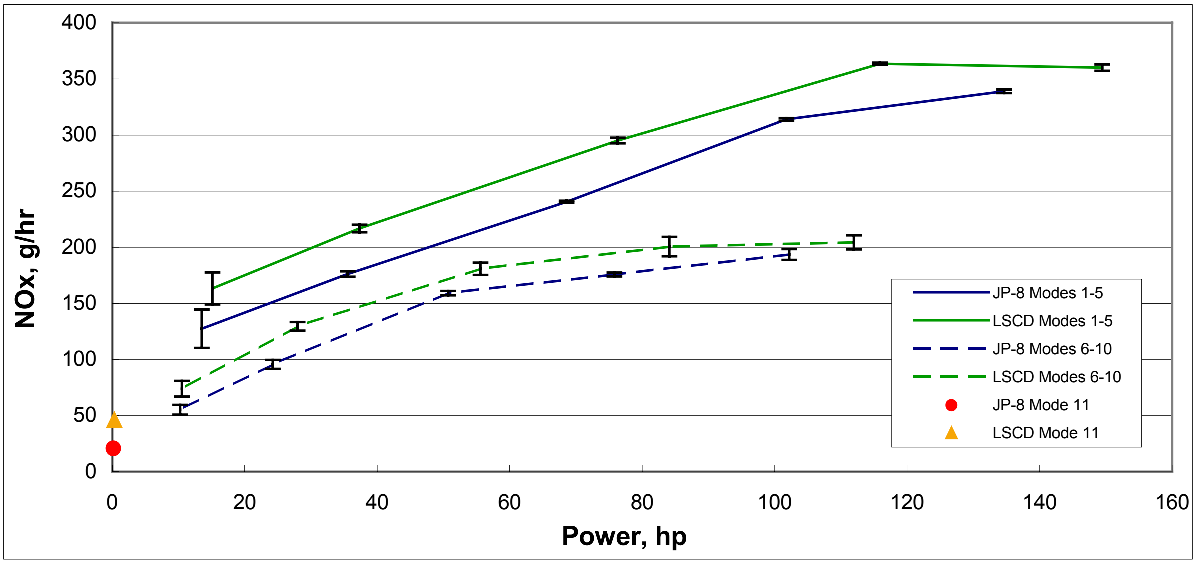



**FIGURE 2. AVERAGE NOx EMISSION RATES FROM GM 6.5L ENGINE FOR 11 STEADY-STATE MODES USING LSCD AND JP-8 (STRAIGHT-LINE CONNECTOR)**

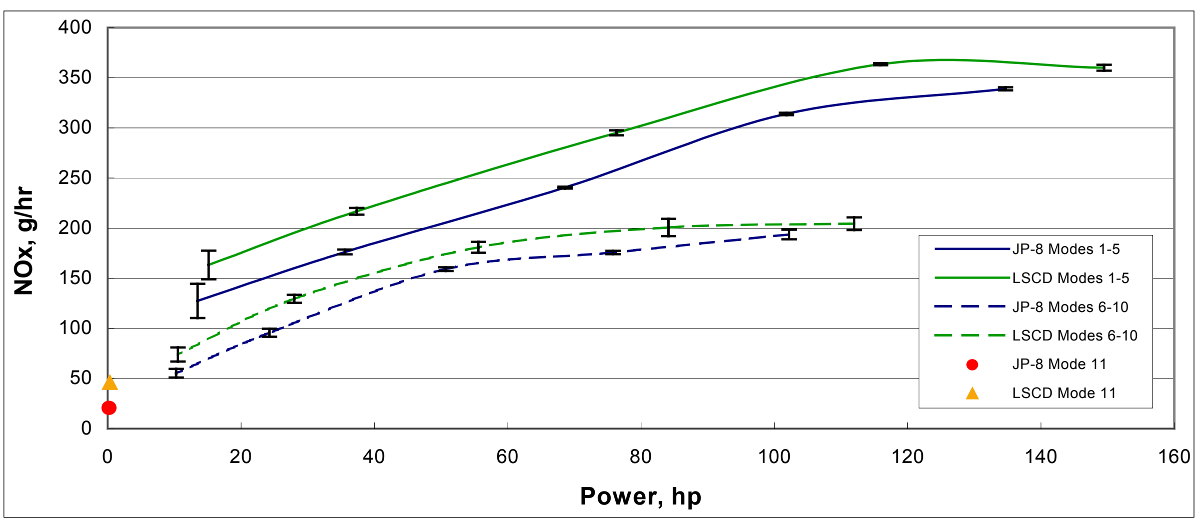



**FIGURE 3. AVERAGE NOx EMISSION RATES FROM GM 6.5L ENGINE FOR 11 STEADY-STATE MODES USING LSCD AND JP-8 (SMOOTHED-LINE CONNECTOR)**

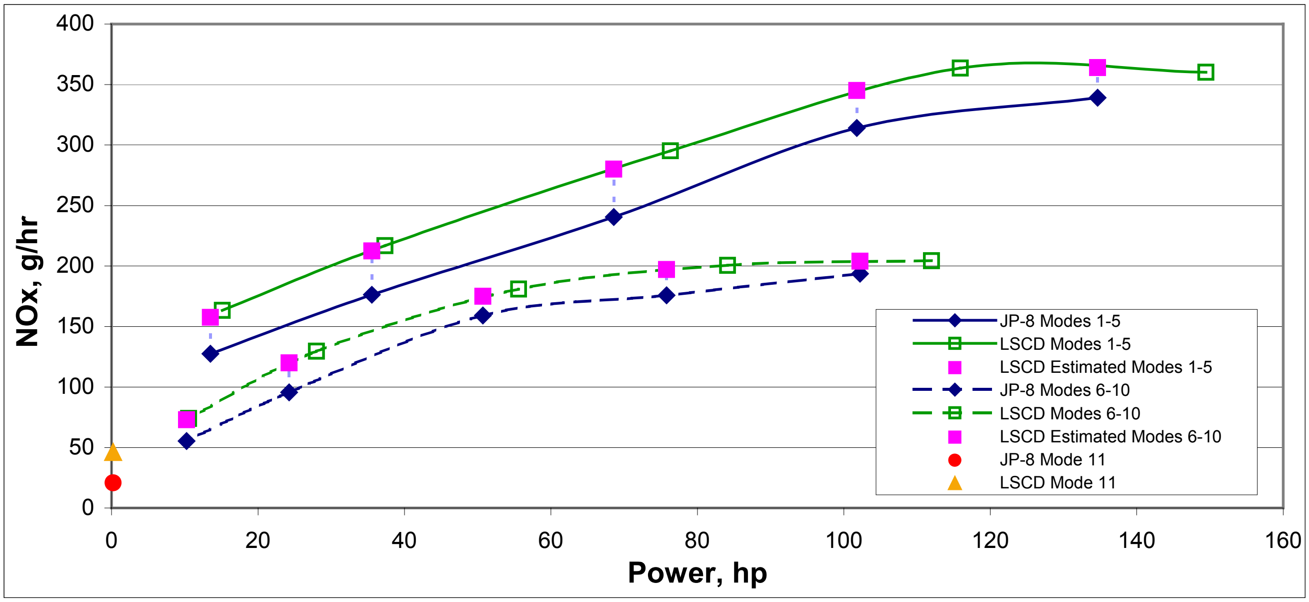



**FIGURE 4. AVERAGE AND ESTIMATED NOx EMISSION RATES FROM GM 6.5L ENGINE FOR 11 STEADY-STATE MODES USING LSCD AND JP-8 (SMOOTHED-LINE CONNECTOR)**

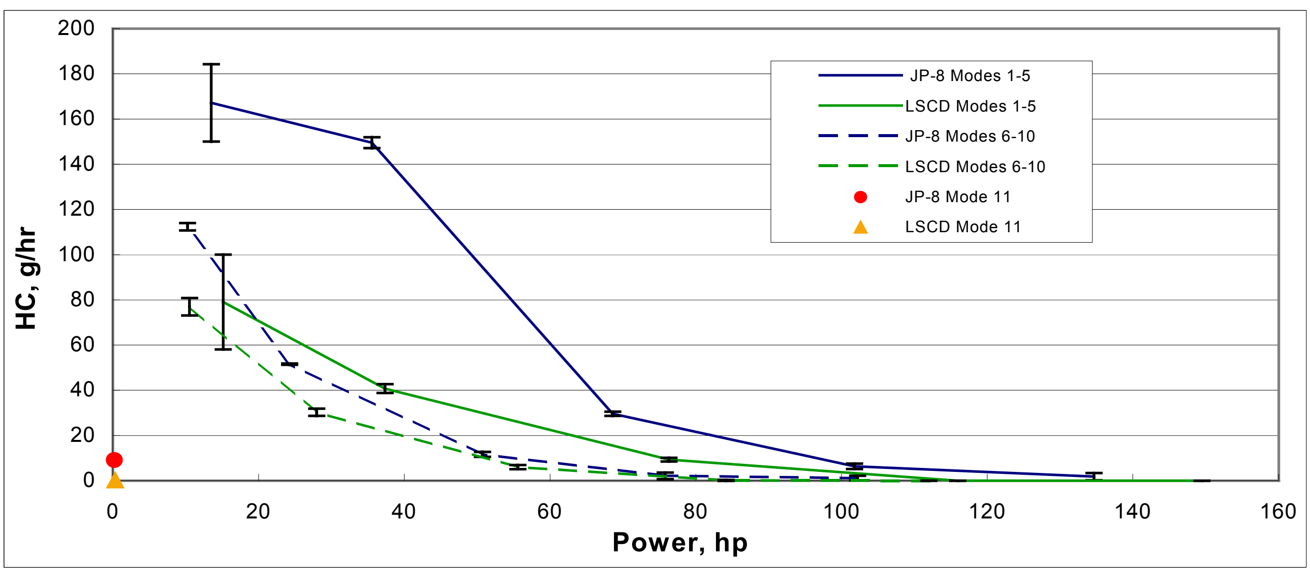



**FIGURE 5. AVERAGE HC EMISSION RATES FROM GM 6.5L ENGINE FOR 11 STEADY-STATE MODES USING LSCD AND JP-8 (STRAIGHT-LINE-CONNECTOR)**

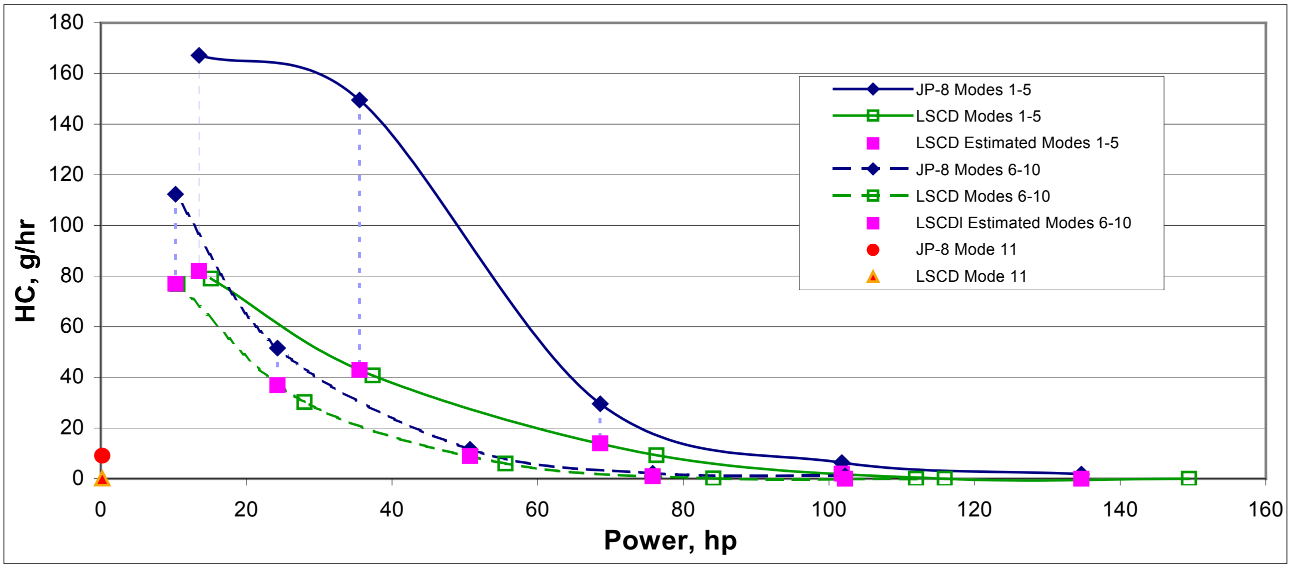



**FIGURE 6. AVERAGE AND ESTIMATED HC EMISSION RATES FROM GM 6.5L ENGINE FOR 11 STEADY-STATE MODES USING LSCD AND JP-8 (SMOOTHED-LINE CONNECTOR)**

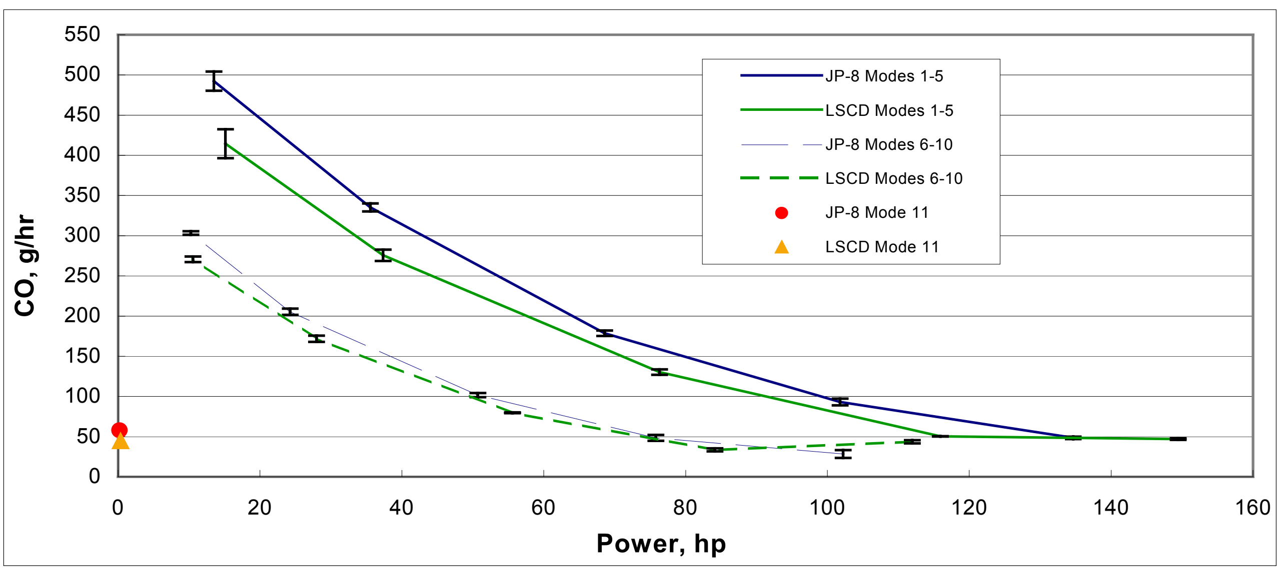



**FIGURE 7. AVERAGE CO EMISSION RATES FROM GM 6.5L ENGINE FOR 11 STEADY-STATE MODES USING LSCD AND JP-8 (STRAIGHT-LINE CONNECTOR)**

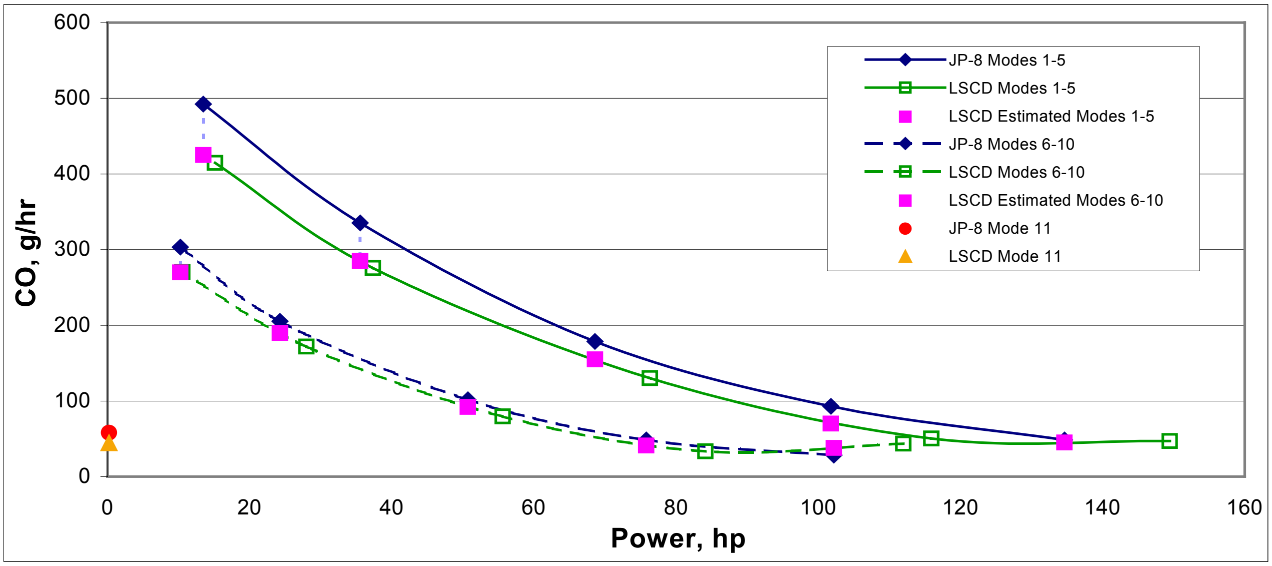



**FIGURE 8. AVERAGE AND ESTIMATED CO EMISSION RATES FROM GM 6.5L ENGINE FOR 11 STEADY-STATE MODES USING LSCD AND JP-8 (SMOOTHED-LINE CONNECTOR)**

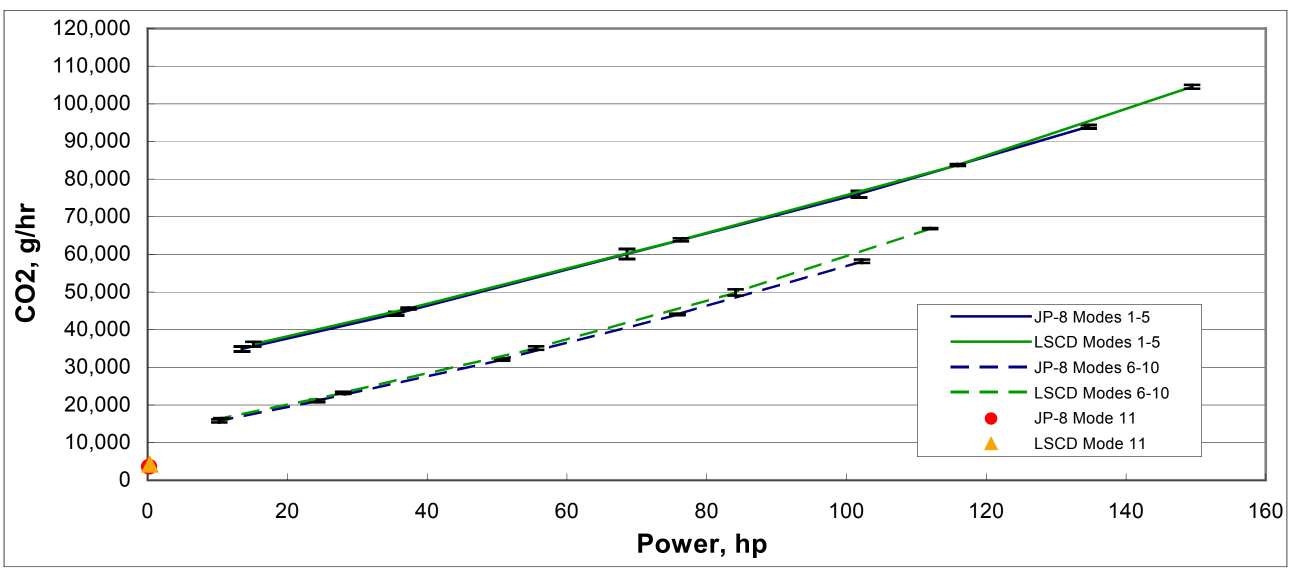



**FIGURE 9. AVERAGE CO2 EMISSION RATES FROM GM 6.5L ENGINE FOR 11 STEADY-STATE MODES USING LSCD AND JP-8 (STRAIGHT-LINE CONNECTOR)**

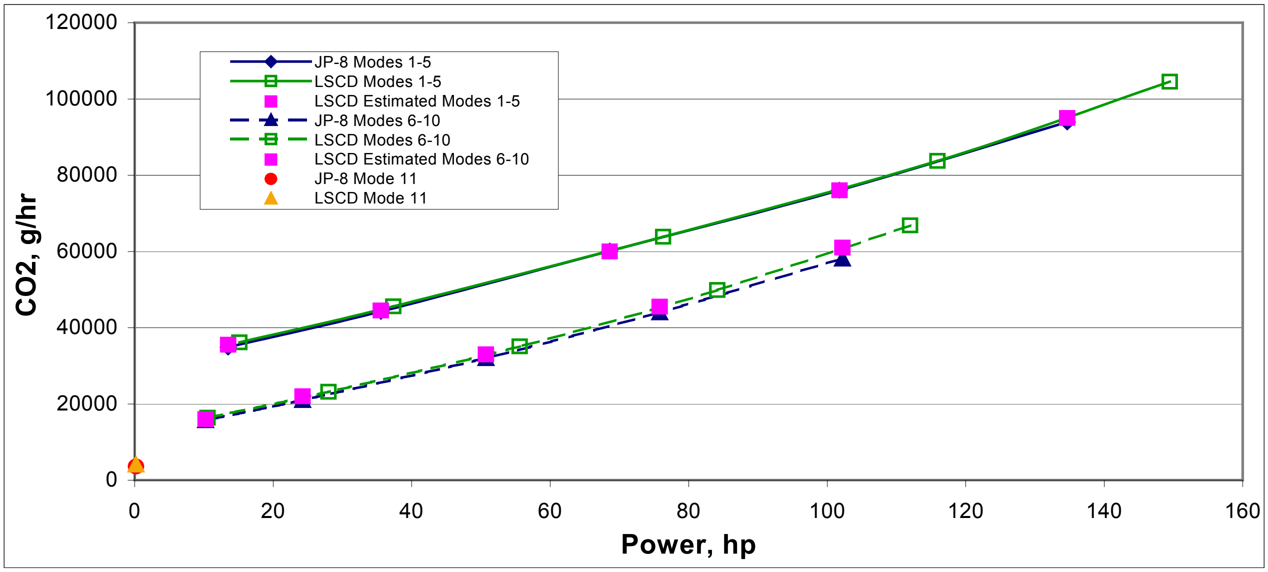



**FIGURE 10. AVERAGE AND ESTIMATED CO2 EMISSION RATES FROM GM 6.5L ENGINE FOR 11 STEADY-STATE MODES USING LSCD AND JP-8 (SMOOTHED-LINE CONNECTOR)**

**TABLE 4. MODAL AND COMPOSITE EMISSION RATES FROM GM 6.5L ENGINE FOR 11 STEADY-STATE MODES USING LSCD AND JP-8**

| Fuel ID | Mode Number | Power hp | Fuel Flow lb/hr | Mass Flow (g/hr) HC | CO | CO2 | NOx | PM | SOF (g/hr) | SOF % | 8-Mode Wt. Factor |
|---|---|---|---|---|---|---|---|---|---|---|---|
| JP-8 | 1 | 134.7 | 65.7 | 1.82 | 48.5 | 93952 | 339 | 6.09 | 1.95 | 32 | 0.15 |
| | 2 | 101.8 | 53.3 | 6.36 | 93.0 | 76030 | 314 | 5.19 | 2.37 | 46 | 0.15 |
| | 3 | 68.6 | 42.3 | 29.62 | 178.6 | 60109 | 241 | 6.49 | 3.95 | 61 | 0.15 |
| | 4 | 35.6 | 31.6 | 149.53 | 335.2 | 44226 | 176 | 8.94 | 7.17 | 80 | - |
| | 5 | 13.5 | 25.3 | 167.18 | 492.3 | 34883 | 127 | 12.39 | 10.26 | 83 | 0.10 |
| | 6 | 102.2 | 40.7 | 1.17 | 28.4 | 58169 | 194 | 8.35 | 4.25 | 51 | 0.10 |
| | 7 | 75.8 | 30.8 | 2.17 | 48.4 | 44042 | 176 | 4.86 | 2.32 | 48 | 0.10 |
| | 8 | 50.7 | 22.5 | 11.65 | 101.6 | 32045 | 159 | 5.11 | 3.18 | 62 | 0.10 |
| | 9 | 24.3 | 15.1 | 51.60 | 205.4 | 21070 | 96 | 7.48 | 5.36 | 72 | - |
| | 10 | 10.2 | 11.6 | 112.35 | 303.3 | 15745 | 55 | 10.29 | 7.53 | 73 | - |
| | 11 | 0.2 | 2.6 | 9.12 | 58.0 | 3575 | 21 | 3.18 | 1.93 | 61 | 0.15 |
| | 8-Mode Composite (g/hp-hr) | | | 0.36 | 1.77 | 742 | 2.90 | 0.09 | 0.05 | 57 | 1.00 |
| LSCD | 1 | 149.5 | 72.5 | 0.00 | 47.0 | 104524 | 360 | 13.22 | 1.90 | 14 | 0.15 |
| | 2 | 115.9 | 58.1 | 0.00 | 50.3 | 83738 | 364 | 6.37 | 1.86 | 29 | 0.15 |
| | 3 | 76.3 | 44.4 | 9.32 | 130.3 | 63867 | 295 | 8.90 | 3.10 | 35 | 0.15 |
| | 4 | 37.3 | 32.0 | 40.75 | 275.6 | 45605 | 217 | 10.79 | 8.26 | 77 | - |
| | 5 | 15.1 | 25.7 | 79.06 | 414.5 | 36123 | 163 | 17.67 | 14.79 | 84 | 0.10 |
| | 6 | 112.0 | 46.4 | 0.00 | 43.6 | 66844 | 204 | 22.21 | 2.78 | 13 | 0.10 |
| | 7 | 84.1 | 34.6 | 0.15 | 33.5 | 49872 | 201 | 5.86 | 2.96 | 51 | 0.10 |
| | 8 | 55.6 | 24.4 | 6.02 | 79.6 | 35099 | 181 | 5.90 | 2.76 | 47 | 0.10 |
| | 9 | 28.0 | 16.3 | 30.27 | 171.8 | 23213 | 130 | 10.05 | 7.40 | 74 | - |
| | 10 | 10.5 | 11.8 | 76.97 | 270.7 | 16381 | 74 | 17.19 | 14.10 | 82 | - |
| | 11 | 0.3 | 2.9 | 0.12 | 44.3 | 4109 | 46 | 2.68 | 1.15 | 43 | 0.15 |
| | 8-Mode Composite (g/hp-hr) | | | 0.13 | 1.26 | 734 | 3.01 | 0.13 | 0.05 | 36 | 1.00 |
| Estimated LSCD | 1 | 134.7 | 65.6 | 0.00 | 45.0 | 95000 | 364 | 9.60 | n/a | | 0.15 |
| | 2 | 101.8 | 53.0 | 2.00 | 70.0 | 76000 | 345 | 6.60 | | | 0.15 |
| | 3 | 68.6 | 41.9 | 14.00 | 155.0 | 60000 | 280 | 9.25 | | | 0.15 |
| | 4 | 35.6 | 31.5 | 43.00 | 285.0 | 44500 | 213 | 11.00 | | | - |
| | 5 | 13.5 | 25.2 | 82.00 | 425.0 | 35500 | 158 | 18.00 | | | 0.10 |
| | 6 | 102.2 | 42.1 | 0.00 | 38.0 | 61000 | 204 | 15.75 | | | 0.10 |
| | 7 | 75.8 | 31.4 | 1.00 | 41.0 | 45500 | 197 | 4.60 | | | 0.10 |
| | 8 | 50.7 | 22.9 | 9.00 | 92.0 | 33000 | 175 | 6.40 | | | 0.10 |
| | 9 | 24.3 | 15.4 | 37.00 | 190.0 | 22000 | 120 | 11.20 | | | - |
| | 10 | 10.2 | 11.8 | 77.00 | 270.0 | 16000 | 73 | 17.25 | | | - |
| | 11 | 0.2 | 2.8 | 0.12 | 44.3 | 4109 | 46 | 2.68 | | | 0.15 |
| | 8-Mode Composite (g/hp-hr) | | | 0.17 | 1.52 | 754 | 3.27 | 0.12 | | | 1.00 |

**Table 4A. Emission Results from a 6.5L GM Heavy-Duty Diesel Engine**

| Fuel ID | Mode Number | Power hp | Brake-Specific Emission Results (g/hp-hr) HC | CO | CO2 | NOx | PM | SOF g/hp-hr | SOF % of PM | 8-Mode Wt. Factor |
|---|---|---|---|---|---|---|---|---|---|---|
| JP-8 | 1 | 134.7 | 0.01 | 0.36 | 698 | 2.52 | 0.05 | 0.01 | 32 | 0.15 |
| | 2 | 101.8 | 0.06 | 0.91 | 747 | 3.09 | 0.05 | 0.02 | 46 | 0.15 |
| | 3 | 68.6 | 0.43 | 2.60 | 876 | 3.51 | 0.09 | 0.06 | 61 | 0.15 |
| | 4 | 35.6 | 4.21 | 9.44 | 1245 | 4.96 | 0.25 | 0.20 | 80 | - |
| | 5 | 13.5 | 12.58 | 36.84 | 2602 | 9.49 | 0.93 | 0.95 | 83 | 0.10 |
| | 6 | 102.2 | 0.01 | 0.28 | 569 | 1.89 | 0.08 | 0.04 | 51 | 0.10 |
| | 7 | 75.8 | 0.03 | 0.64 | 581 | 2.32 | 0.06 | 0.03 | 48 | 0.10 |
| | 8 | 50.7 | 0.23 | 2.00 | 632 | 3.14 | 0.10 | 0.06 | 62 | 0.10 |
| | 9 | 24.3 | 2.13 | 8.47 | 869 | 3.94 | 0.31 | 0.22 | 72 | - |
| | 10 | 10.2 | 11.03 | 29.75 | 1542 | 5.40 | 1.01 | 0.74 | 73 | - |
| | 11 | 0.2 | - | - | - | - | - | - | - | 0.15 |
| | 8-Mode Composite (g/hp-hr) | | 0.36 | 1.77 | 742 | 2.90 | 0.09 | 0.05 | 57 | 1.00 |
| LSCD | 1 | 149.5 | 0.00 | 0.31 | 699 | 2.41 | 0.09 | 0.01 | 14 | 0.15 |
| | 2 | 115.9 | 0.00 | 0.43 | 722 | 3.14 | 0.05 | 0.02 | 29 | 0.15 |
| | 3 | 76.3 | 0.12 | 1.71 | 837 | 3.87 | 0.12 | 0.04 | 35 | 0.15 |
| | 4 | 37.3 | 1.09 | 7.38 | 1222 | 5.81 | 0.29 | 0.22 | 77 | - |
| | 5 | 15.1 | 5.23 | 27.39 | 2388 | 10.80 | 1.17 | 0.98 | 84 | 0.10 |
| | 6 | 112.0 | 0.00 | 0.39 | 597 | 1.83 | 0.20 | 0.02 | 13 | 0.10 |
| | 7 | 84.1 | 0.00 | 0.40 | 593 | 2.38 | 0.07 | 0.04 | 51 | 0.10 |
| | 8 | 55.6 | 0.11 | 1.43 | 631 | 3.25 | 0.11 | 0.05 | 47 | 0.10 |
| | 9 | 28.0 | 1.08 | 6.14 | 830 | 4.63 | 0.36 | 0.26 | 74 | - |
| | 10 | 10.5 | 7.33 | 25.75 | 1558 | 7.03 | 1.64 | 1.35 | 82 | - |
| | 11 | 0.3 | - | - | - | - | - | - | - | 0.15 |
| | 8-Mode Composite (g/hp-hr) | | 0.13 | 1.26 | 734 | 3.01 | 0.13 | 0.05 | 36 | 1.00 |
| LSCD Est | 1 | 134.7 | 0.00 | 0.31 | 700 | 2.75 | 0.07 | n/a | | 0.15 |
| | 2 | 101.8 | 0.00 | 0.60 | 750 | 3.37 | 0.07 | | | 0.15 |
| | 3 | 68.6 | 0.20 | 2.30 | 880 | 4.12 | 0.13 | | | 0.15 |
| | 4 | 35.6 | 1.30 | 8.60 | 1300 | 6.10 | 0.32 | | | - |
| | 5 | 13.5 | 5.45 | 29.00 | 2575 | 11.37 | 1.27 | | | 0.10 |
| | 6 | 102.2 | 0.00 | 0.39 | 600 | 2.00 | 0.15 | | | 0.10 |
| | 7 | 75.8 | 0.00 | 0.50 | 600 | 2.62 | 0.06 | | | 0.10 |
| | 8 | 50.7 | 0.18 | 1.75 | 650 | 3.40 | 0.13 | | | 0.10 |
| | 9 | 24.3 | 2.00 | 9.00 | 980 | 5.00 | 0.52 | | | - |
| | 10 | 10.2 | 7.40 | 26.00 | 1600 | 7.12 | 1.65 | | | - |
| | 11 | 0.2 | - | - | - | - | - | | | 0.15 |
| | 8-Mode Composite (g/hp-hr) | | 0.17 | 1.52 | 754 | 3.27 | 0.12 | | | 1.00 |

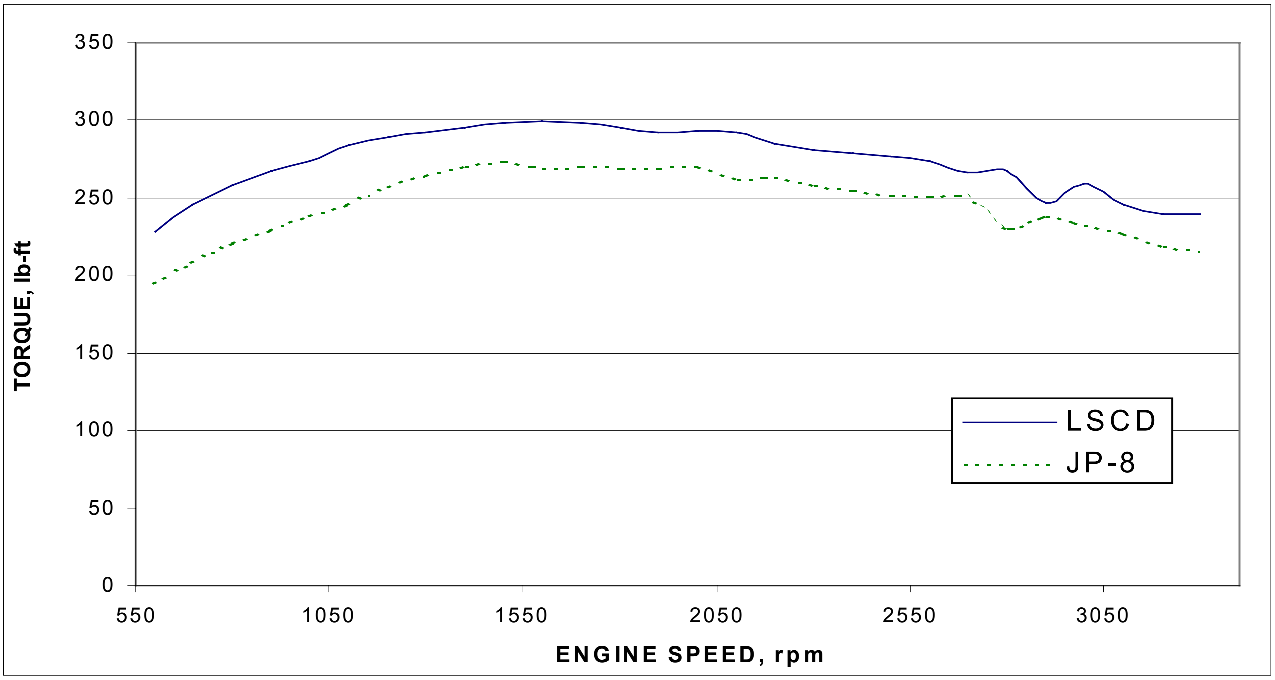



**FIGURE 11. TRANSIENT TORQUE MAPS ON TWO FUELS FROM A 2002 GM 6.5L HEAVY-DUTY DIESEL ENGINE**

## TABLE 5. TORQUE MAPS FROM A 2002 GM 6.5L HEAVY-DUTY DIESEL ENGINE USING TWO FUELS

| ENGINE SPEED, rpm | TORQUE, lb-ft | |
|---|---|---|
| | Fuel: LSCD EM-4816-F | Fuel: JP-8 AL-26936 |
| | MAP # 688 | MAP # 659 |
| 600 | 228 | 196 |
| 700 | 246 | 209 |
| 800 | 258 | 221 |
| 900 | 267 | 229 |
| 1000 | 274 | 238 |
| 1100 | 284 | 245 |
| 1200 | 289 | 257 |
| 1300 | 293 | 264 |
| 1400 | 296 | 270 |
| 1500 | 298 | 274 |
| 1600 | 300 | 270 |
| 1700 | 298 | 271 |
| 1800 | 295 | 269 |
| 1900 | 292 | 270 |
| 2000 | 294 | 270 |
| 2100 | 292 | 262 |
| 2200 | 285 | 263 |
| 2300 | 280 | 258 |
| 2400 | 278 | 255 |
| 2500 | 277 | 252 |
| 2600 | 273 | 251 |
| 2700 | 267 | 250 |
| 2800 | 267 | 230 |
| 2900 | 246 | 238 |
| 3000 | 259 | 232 |
| 3100 | 246 | 227 |
| 3200 | 240 | 219 |
| 3300 | 240 | 216 |

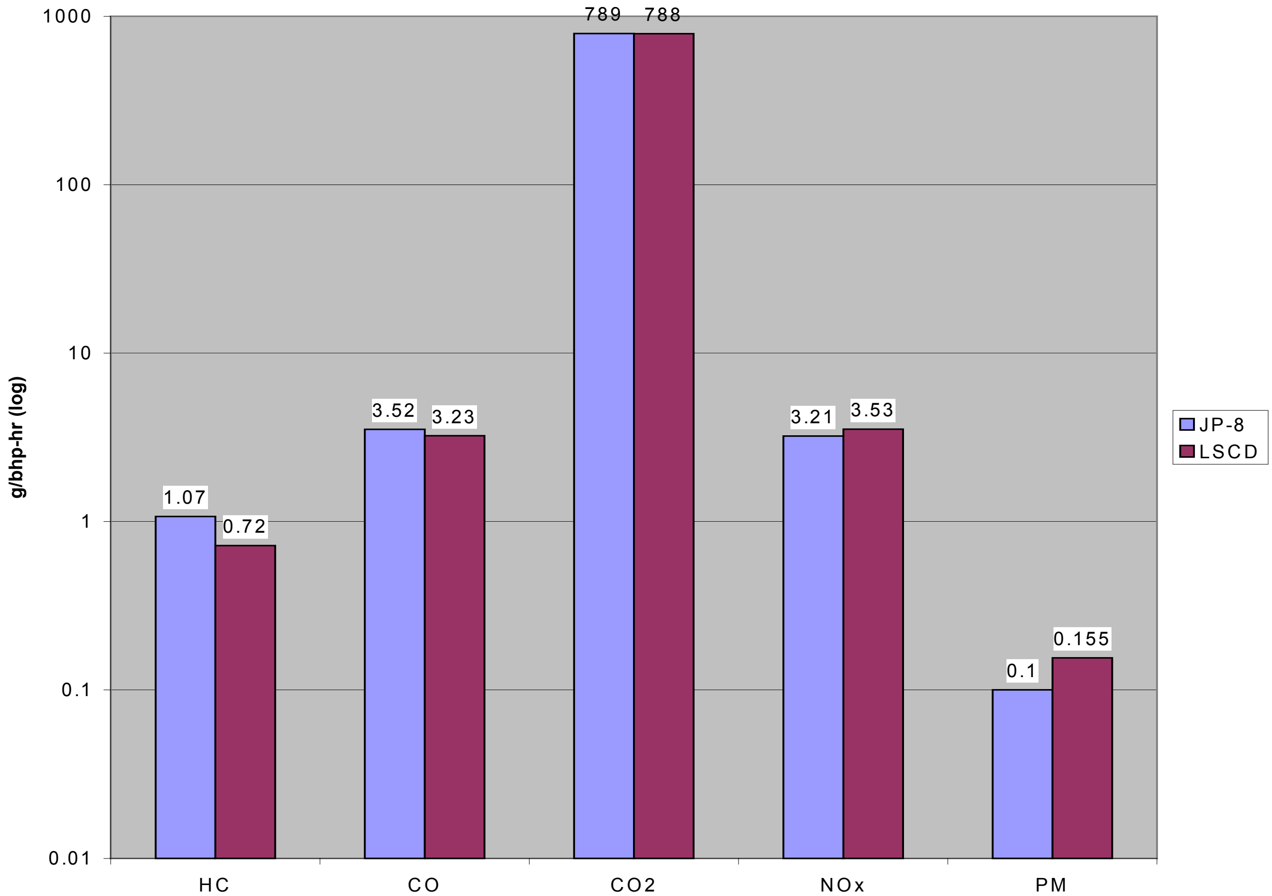



**FIGURE 12. EXHAUST EMISSIONS NONROAD TRANSIENT TEST CYCLE (SAT)**

**TABLE 6. TRANSIENT EMISSION RATES FROM GM 6.5L ENGINE FOR SAT NONROAD TESTS USING JP-8**

| Fuel ID | Test Number | Work hp-hr | BSFC lb/hp-hr | Brake Specific Emissions (g/hp-hr) | | | | | SOF (g/hp-hr) | SOF % |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | HC | CO | CO2 | Nox | PM | | |
| JP-8 | 684 SATJP-8a | 16.4 | 0.553 | 1.00 | 3.37 | 786 | 3.24 | 0.097 | 0.065 | 67 |
| | 685 SATJP-8b | 16.0 | 0.556 | 1.07 | 3.55 | 791 | 3.14 | 0.099 | 0.082 | 83 |
| | 686 SATJP-8c | 15.9 | 0.556 | 1.13 | 3.63 | 790 | 3.26 | 0.103 | 0.081 | 79 |
| | Average | 16.1 | 0.555 | 1.07 | 3.52 | 789 | 3.21 | 0.100 | 0.076 | 76 |

### 3.2.3 PAH Emissions

Particulate filters were collected during the ISO 8178 11-mode tests using low sulfur reference diesel fuel and JP-8. Triplicate exhaust emission tests were conducted for each of the 11 modes. Each particulate filter was extracted to remove SOF of the particulate matter (PM). The SOF was further extracted in a Soxhlet using a solvent mixture of 30 percent toluene/ 70 percent ethanol by volume to remove PAH compounds. At the beginning of the extraction, a PAH surrogate spiking solution (internal standard) containing three deuterated

PAHs [benzo(b)fluoranthene-d12, benzo(a)anthracene-d12, and dibenz(a,h)anthracene-d14 at 100 nanograms each] was spiked into the sample. The sample extracts were blown down to a final volume of 100 microliters (uL). Two or three characteristic ions of each PAH were monitored using GC/MS/SIM (selected ion monitoring) analysis. The PAHs were analyzed in the positive ion electron impact (PI/EI) mode. A composite extract was prepared for each of the 11 modes using equal amounts of the triplicate PAH extract. Duplicate PAH analyses were made for the composite extracts for each fuel.

There are 19 PAH's (response variables, shown in Table 7) for each of the 11 ISO 8178 modes. Raw data were converted into power specific emission rates for each PAH type. Figure 13 shows a log scale plot of the PAH's from the PM for JP-8 and LSCD. The values are the weighted 8-mode results. Also shown are the results for JP-8 operated following the transient nonroad (SAT) cycle. Identity of the PAH numbers are shown in Table 7. The JP-8 fuel produced lower levels of exhaust PAH's than the LSCD fuel, for most but not all PAH types.

Figure 14 shows a typical plot of the brake specific amount of PAH-2 (2-methylnaphthalene) for each operating mode (except idle). PAH-2 was extracted from the exhaust PM of JP-8 and LSCD. Table 8 shows the mode number associated with various speed/load combinations. Similar plots were prepared for all 19 PAH's, and are presented in Appendix E.

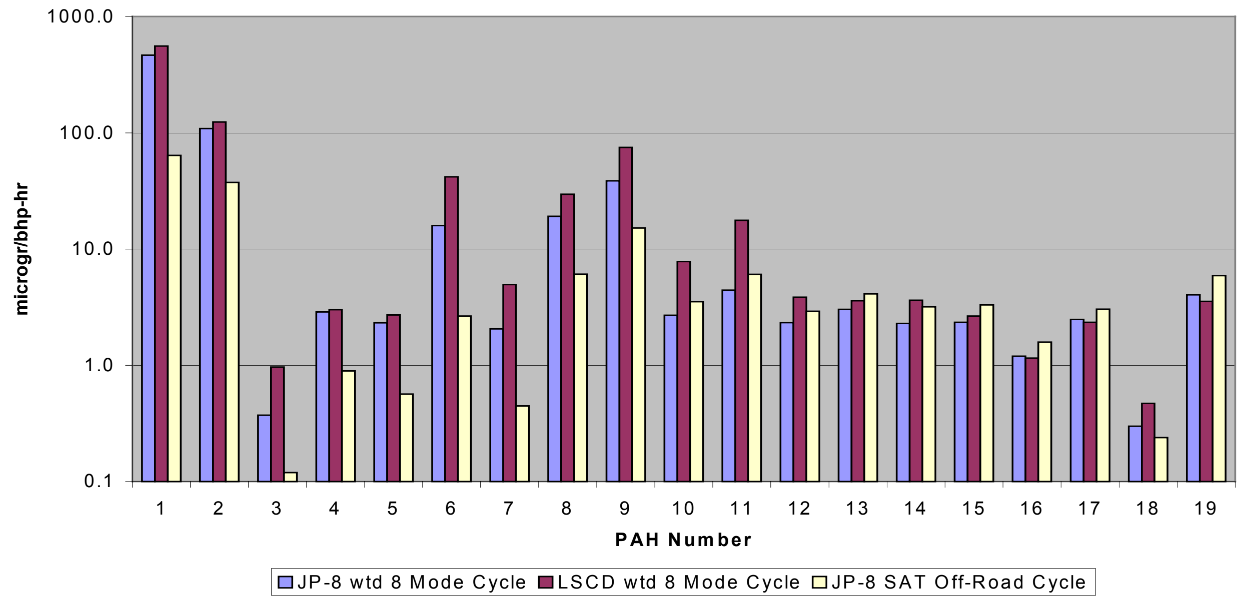



**FIGURE 13. PAH's BY TEST CYCLE**

| Table 7. PAH Identification | |
|---|---|
| PAH-1 | Naphthalene |
| PAH-2 | 2-Methylnaphthalene |
| PAH-3 | Acenaphthylene |
| PAH-4 | Acenaphthene |
| PAH-5 | Fluorene |
| PAH-6 | Phenanthrene |
| PAH-7 | Anthracene |
| PAH-8 | Fluoranthene |
| PAH-9 | Pyrene |
| PAH-10 | Benzo (a) anthracene |
| PAH-11 | Chrysene |
| PAH-12 | Benzo (b) fluoranthene |
| PAH-13 | Benzo (k) fluoranthene |
| PAH-14 | Benzo (e) pyrene |
| PAH-15 | Benzo (a) pyrene |
| PAH-16 | Perylene |
| PAH-17 | Indeno (1, 2, 3-cd) pyrene |
| PAH-18 | Dibenzo (a, h) anthracene |
| PAH-19 | Benzo (g, h, i) perylene |

## Table 8. Speed and Load for Each Mode

| Mode | Speed/% load |
|---|---|
| 1 | Rated/100 |
| 2 | Rated/75 |
| 3 | Rated/50 |
| 4 | Rated/25 |
| 5 | Rated/10 |
| 6 | Intermediate/100 |
| 7 | Intermediate/75 |
| 8 | Intermediate/50 |
| 9 | Intermediate/25 |
| 10 | Intermediate/10 |

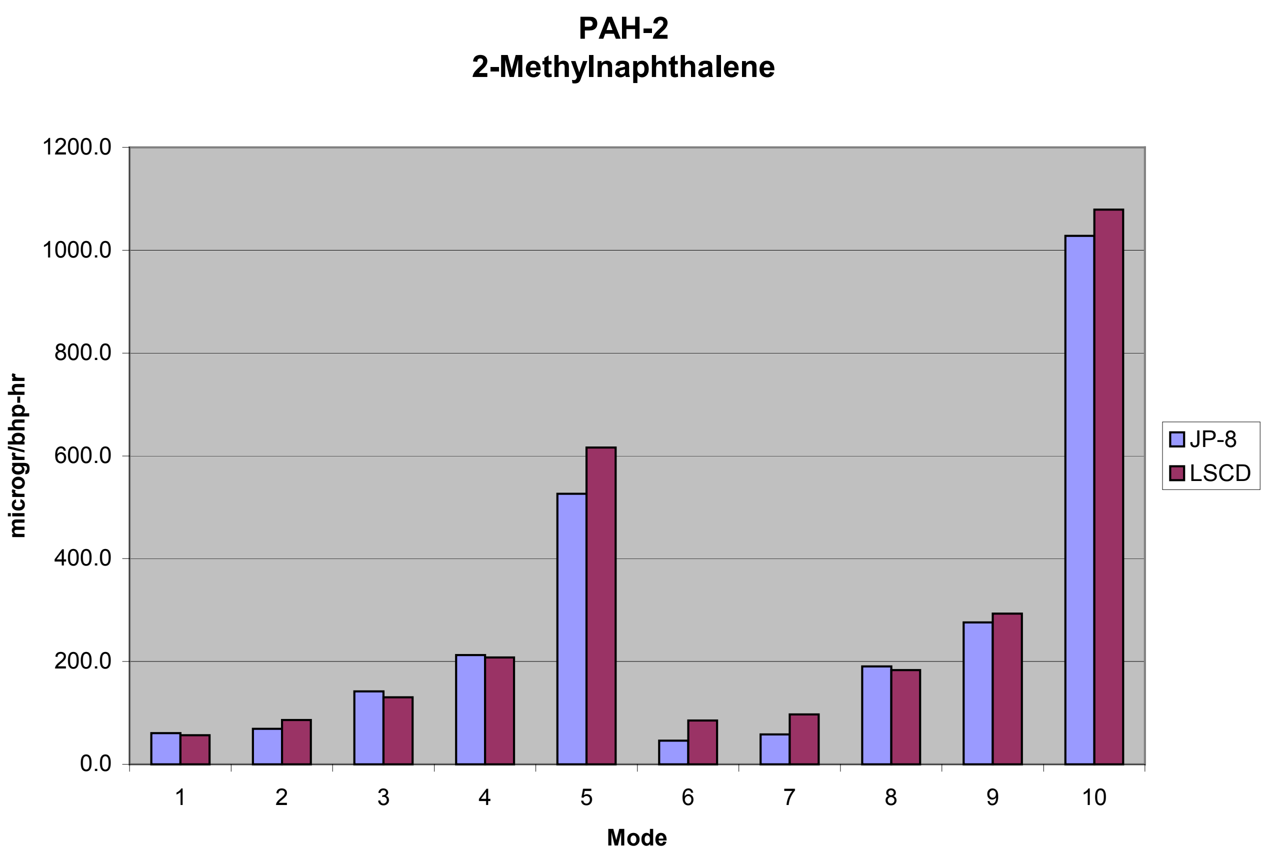



**FIGURE 14. PAH-2**

## 4.0 SUMMARY

Emission results are summarized in Table 9 and Figure 15. This table lists the 8-mode composite results for JP-8, LSCD, and the average SAT transient results for JP-8. JP-8 produced more HC and CO compared to the LSCD for the 8-Mode composite, but JP-8 produced lower levels of NOx and PM. Comparing the results with JP-8 to those estimated for LSCD at the same JP-8 loads, the JP-8 produced 11 percent less NOx and 28 percent less PM compared to the Estimated LSCD. Considering only JP-8, transient nonroad cycle emissions were all notably higher than the 8-mode composite levels.

### TABLE 9. SUMMARY OF EMISSION RESULTS FROM GM 6.5L ENGINE FOR 11-MODE STEADY-STATE AND SAT TRANSIENT NONROAD TESTS USING LSCD AND JP-8

| Test | Fuel | Brake Specific Emissions (g/hp-hr) | | | | | | BSFC |
|---|---|---|---|---|---|---|---|---|
| Type | ID | HC | CO | CO2 | NOx | PM | SOF | lb/hp-hr |
| 8-Mode Composite | JP-8 | 0.36 | 1.77 | 742 | 2.90 | 0.089 | 0.050 | 0.522 |
| 8-Mode Composite | LSCD | 0.13 | 1.26 | 734 | 3.01 | 0.126 | 0.045 | 0.569 |
| 8-Mode Composite | Estimated LSCD | 0.17 | 1.52 | 754 | 3.27 | 0.124 | n/a | 0.524 |
| SAT 3-Test Average | JP-8 | 1.07 | 3.52 | 789 | 3.21 | 0.100 | 0.076 | 0.555 |

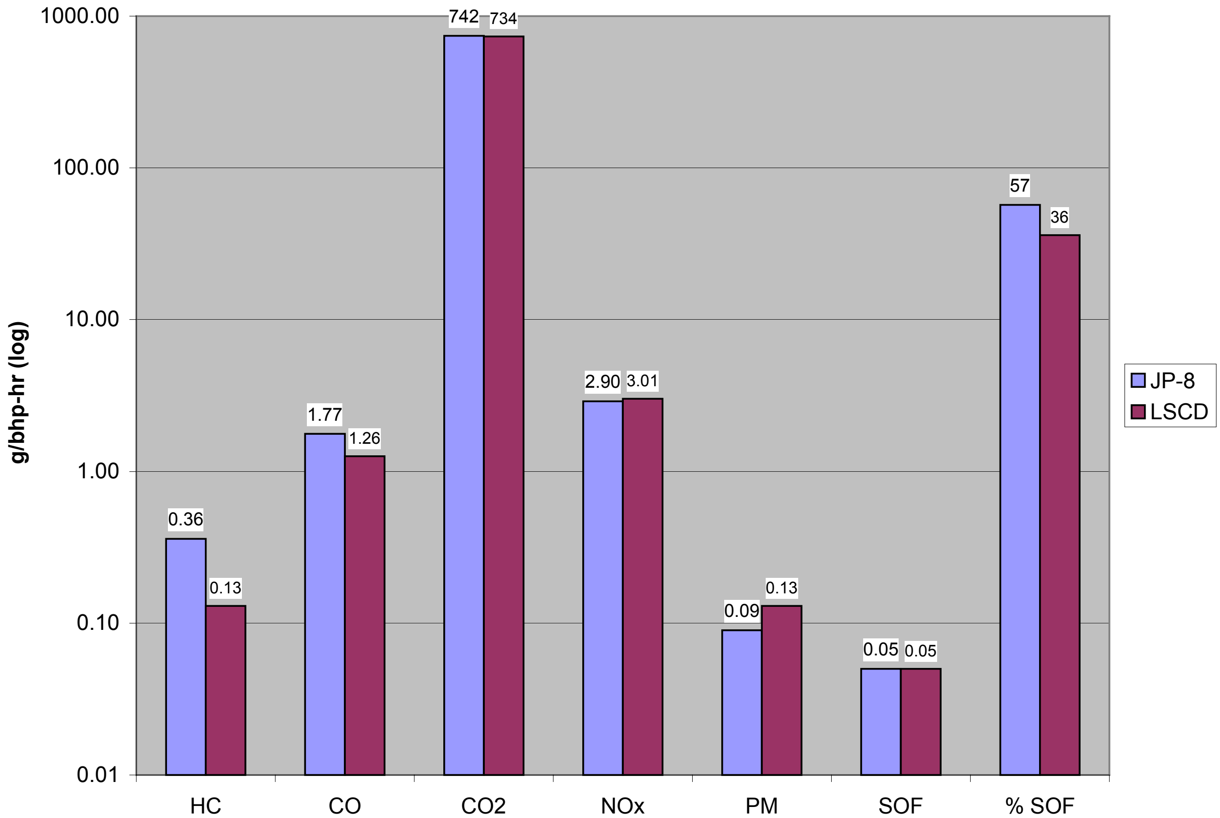



**FIGURE 15. WEIGHTED 8-MODE EXHAUST EMISSIONS**

The JP-8 had lower levels of exhaust PAH's than the LSCD fuel for most PAH types. Benzo (a) pyrene (BAP) is of particular interest because it has been shown to be carcinogenic to experimental animals (3). Compared to JP-8, substantially more BAP was produced by the LSCD at the 10% load modes, i.e., modes 5 and 10, as shown in Figure 16.

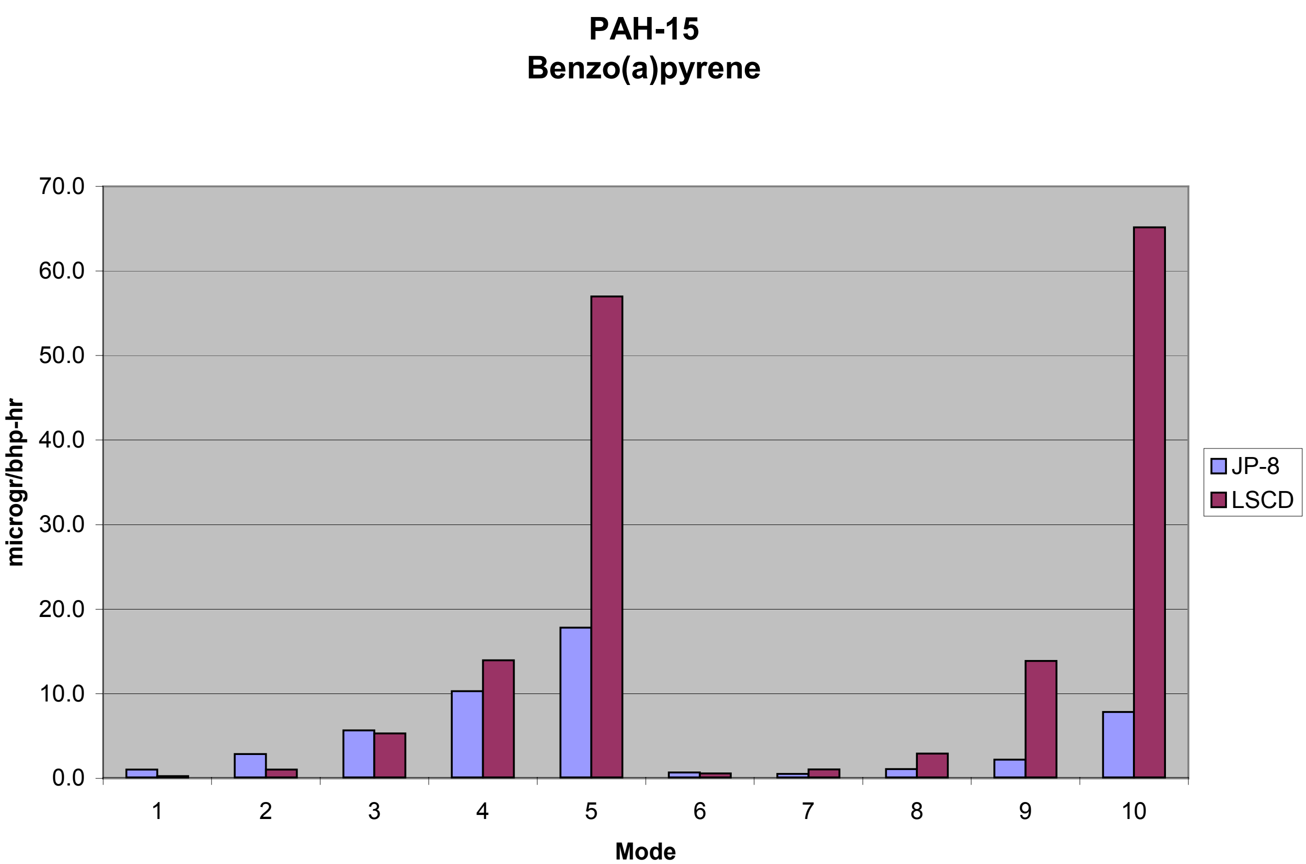



**FIGURE 16. BAP EMISSION FROM PARTICULATE MATTER**

## 5.0 REFERENCES


1. EPA Federal Test Prodecure (FTP), as specified in the Code of Federal Regulations (CFR), Title 40, Part 89, Subpart E, titled CONTROL OF EMISSIONS FROM NEW AND IN-USE NONROAD COMPRESSION-IGNITION ENGINES: EXHAUST EMISSION TEST PROCEDURES.

2. EPA Federal Test Procedure, as specified in the CFR, Title 40, Part 86, Subpart N with the exception of replacing the EPA "ENGINE DYNAMOMETER SCHEDULE FOR HEAVY-DUTY DIESEL ENGINES" given in the CFR, Title 40, Appendix I, Subpart F(2) with the purposed San Antonio Transient (SAT) engine dynamometer schedule.

3. International Agency for Research on Cancer (IARC)-SUMMARIES AND EVALUATIONS, Vol. 32 (1983) p. 211.

# APPENDIX A

## 6.5L GM HEAVY-DUTY DIESEL ENGINE SPECIFICATIONS

## TABLE A-1. ENGINE SPECIFICATIONS

| | | | | | |
|---|---|---|---|---|---|
| **Make: GM Diesel used in HMMWV** | | **Displacement: 6.5 liters** | | | |
| **Model:** | | **Serial Number:** 2722 **Mechanical Injection** | | | |
| **NO.** | **TEST PARAMETER** | **SPECIFICATION** | | | |
| 1 | Rated Speed | 3400 | | | rpm |
| 2 | Rated Power | 160 +/-10 | | | hp |
| 3 | Fuel Rate at Rated Speed and Power | 80 | | | lb/hr |
| 4 | Fuel Temp. at Rated Speed and Power | min. max. | | | °F |
| 5 | Rated Torque Speed | 1700 | | | rpm |
| 6 | Rated Torque | 290 +/-15 | | | lb-ft |
| 7 | Fuel Rate at Rated Torque Speed and Torque | 47 | | | lb/hr |
| 8 | High Idle *(governed)* | 3900 | | | rpm |
| 9 | Low Idle *(curb idle)* | 700 | | | rpm |
| 10 | CITT @ rpm *(automatic transmission application)* | NA lb-ft @ | | | rpm |
| 11 | Cranking Speed | 150 | | | rpm |
| 12 | Water Outlet Temperature | thermostat +/-5 | | | °F |
| 13 | Pressure Drop Across Intercooler | NA | | | "$H_2O$ |
| 14 | Air Temperature After Intercooler | min. NA max. NA | | | °F |
| 15 | Engine Oil Viscosity *(SAE rating)* | 15W40 | | | |
| 16 | Engine Coolant Type *(water, %water + %glycol, etc.)* | Water + Glycol | | | |
| 17 | **Intake and Exhaust Restrictions** | Part 86 Transient | Federal Smoke | Part 89[a] Nonroad | |
| 18 | Intake Restriction[b] +/-(1.0 "$H_2O$) | | | 15.3@ Rated | "$H_2O$ |
| 19 | Exhaust Restriction[b] +/- ( 0.1 "Hg) | | | 7.5@ Rated | "Hg |
| 20 | Intake Restriction Location from Inlet[c] | | | | Inches |
| 21 | Exhaust Restriction Location from Outlet[c] | | | | Inches |

[a] Or other steady-state emissions test, as follows: ISO-8178 11-MODE

[b] Provide values applicable to project. (Tolerances as shown, unless otherwise specified.) and specify tubing diameters at probes in inches as follows: Intake ________ Exhaust ________ .

[c] From Turbo if turbocharged or from Manifold if naturally aspirated.

SwRI Department of Emissions Research

# APPENDIX B

# BREAK-IN INSTRUCTIONS

## TABLE B-1. "BREAK-IN" INSTRUCTIONS SUPPLIED BY TFLFR

**Break-in Instructions**

Start engine and warm up at idle:

| RPM | Load,ft-lbs | Duration, Minutes |
|---|---|---|
| 1500 | 100 | 15 |
| 2500 | 150 | 15 |
| 3000 | 200 | 30 |
| 3400 | WOT | 30 |

Test Conditons:

Fuel inlet temp 95 F
Coolant outlet temp 180 F
Oil sump temp. keep below 250F

The service accumulation schedule is:

| Step No. | Eng. Load,% | PM | Duration |
|---|---|---|---|
| 1. | 0 | 700 | 60 seconds |
| 2. | 10% | 1000 | 10 seconds |
| 3. | 50% | 2000 | 30 seconds |
| 4. | 75% | 3400 | 8 hours |
| 5. | Check fluid levels at least once every 8 hours | | |
| 6. | Repeat steps 1-4 for 100 hours total | | |
| 7. | Change engine oil at 25, 50 and 75 hours | | |

# APPENDIX C

## 11-MODE STEADY-STATE EMISSION RESULTS FROM 6.5L GM HEAVY-DUTY DIESEL ENGINE USING JP-8 AND LSCD

**INSERT PDF FILE HERE**

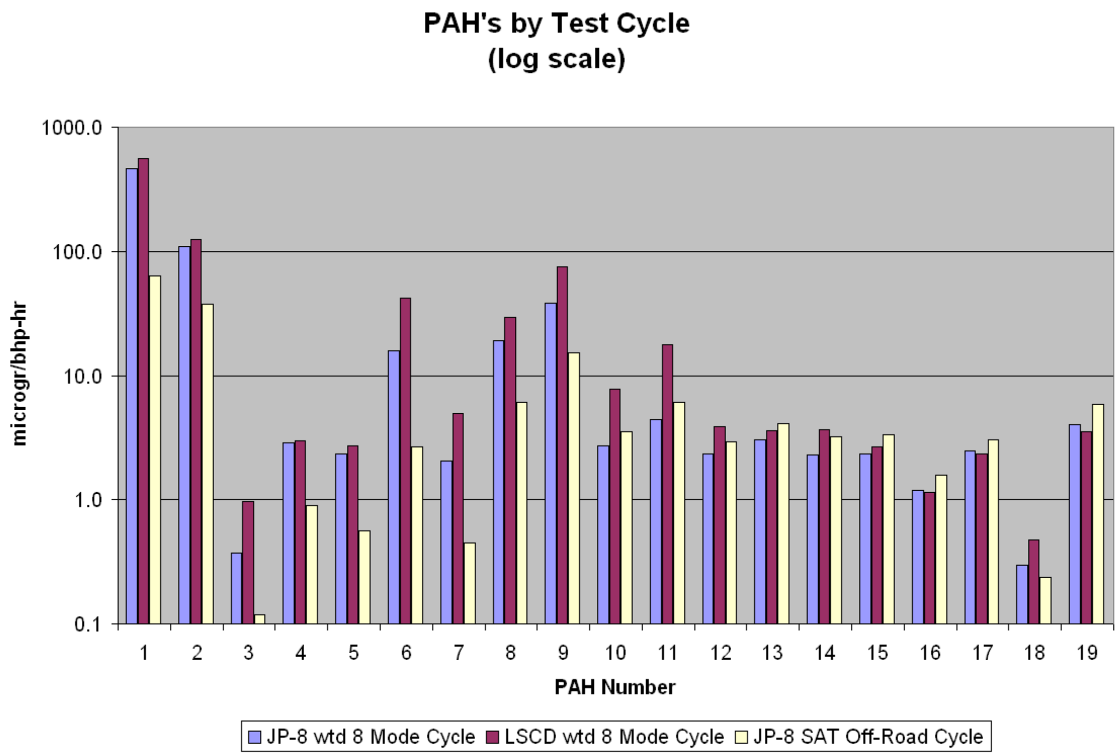
# APPENDIX D

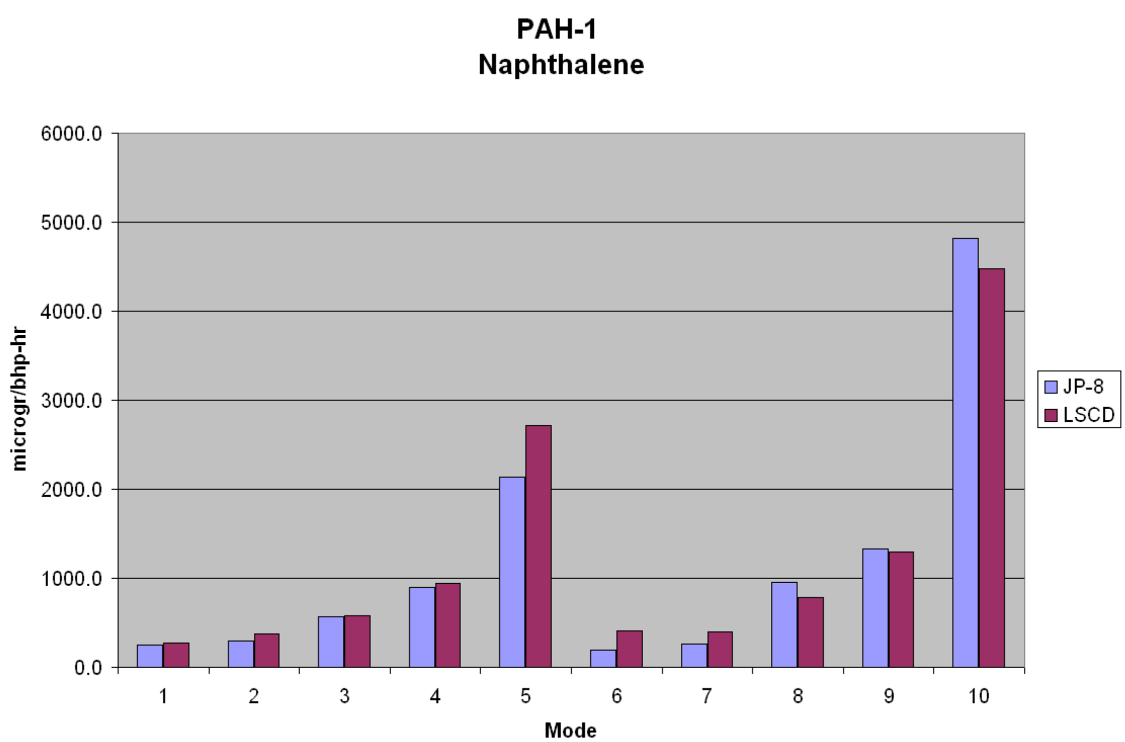
# SAT NONROAD TRANSIENT EMISSION RESULTS FROM 6.5L GM HEAVY-DUTY DIESEL ENGINE USING JP-8

**INSERT PDF FILE HERE**

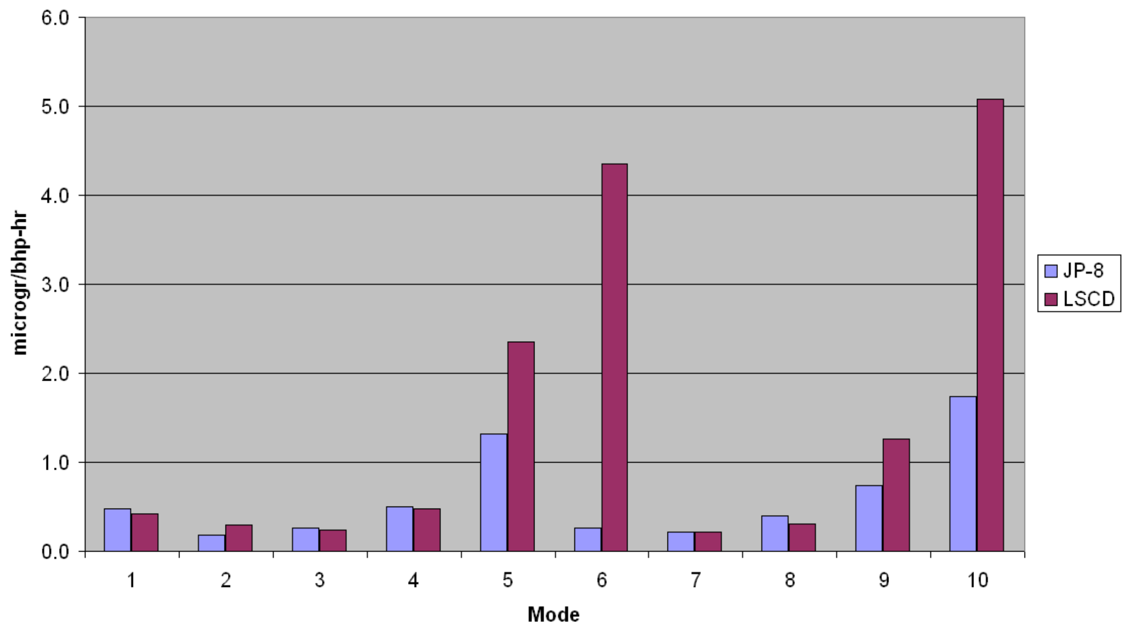
# APPENDIX E

# BRAKE-SPECIFIC PAH'S

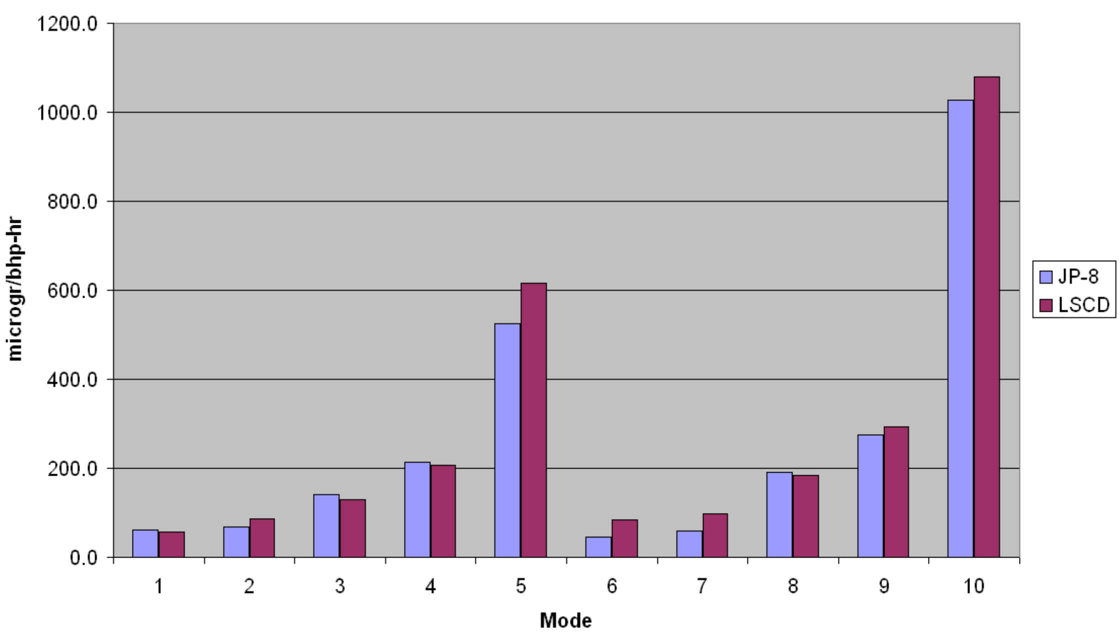

PAH's by Test Cycle
(log scale)
1000.0
100.0
10.0
1.0
0.1
microgr/bhp-hr
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
PAH Number
JP-8 wtd 8 Mode Cycle
LSCD wtd 8 Mode Cycle
JP-8 SAT Off-Road Cycle

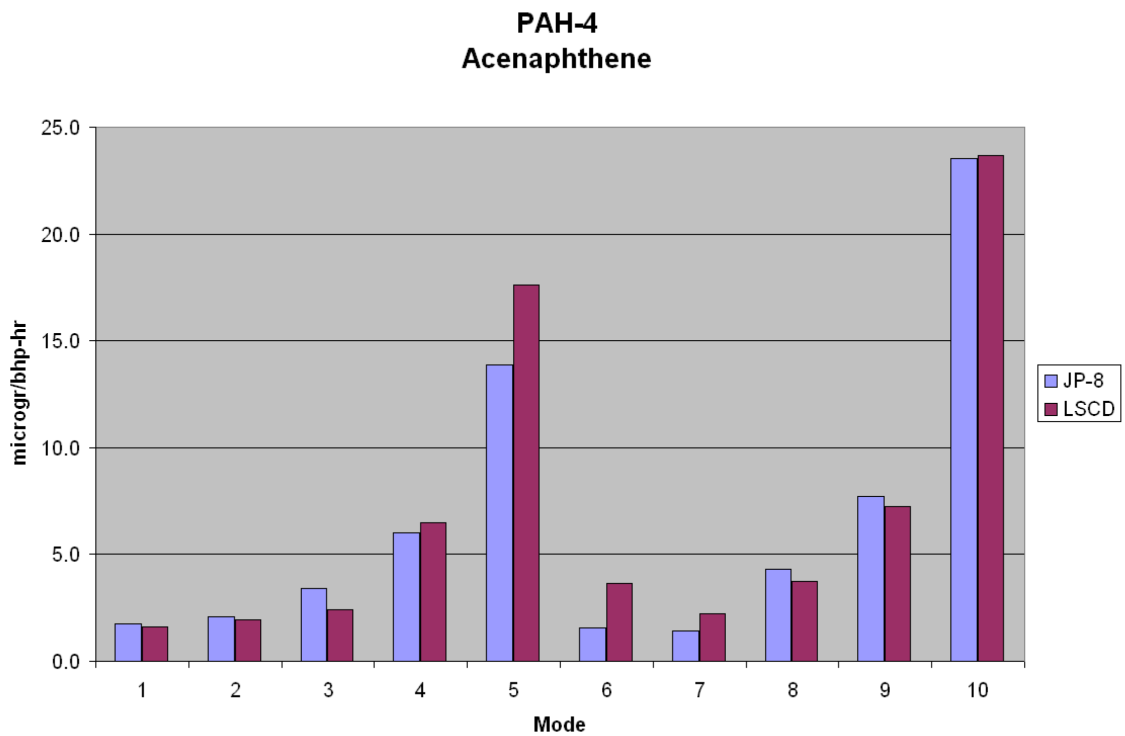

PAH-1
Naphthalene
6000.0
5000.0
4000.0
3000.0
2000.0
1000.0
0.0
microgr/bhp-hr
1 2 3 4 5 6 7 8 9 10
Mode
JP-8
LSCD

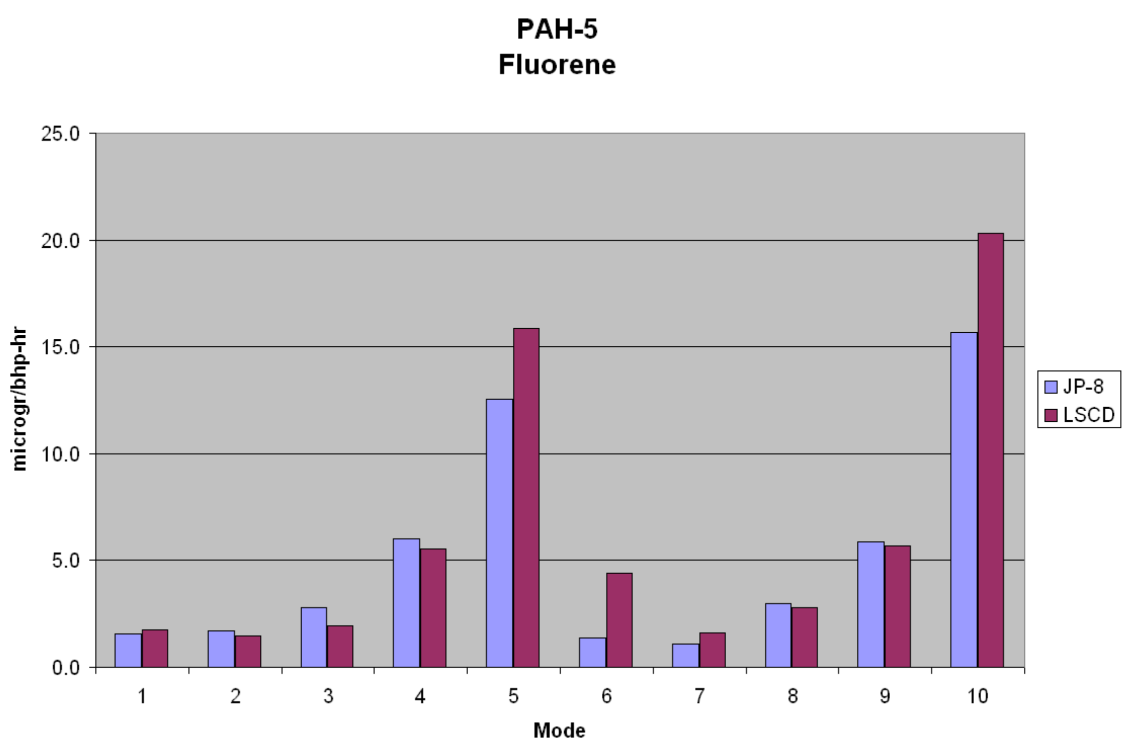
## PAH-3
## Acenaphthylene



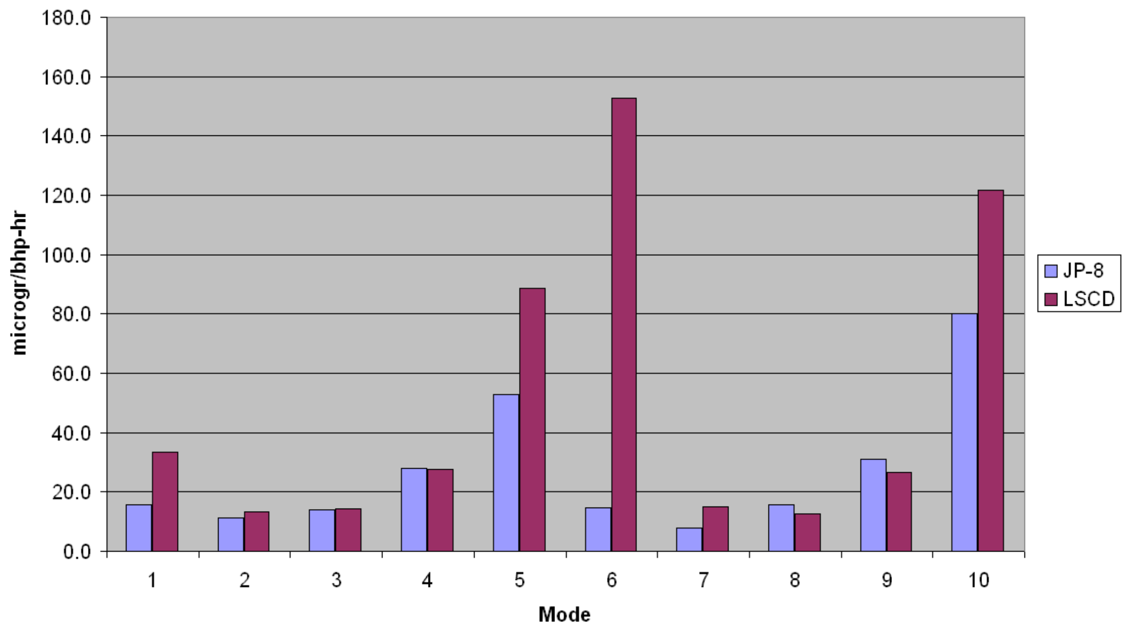

## PAH-2
## 2-Methylnaphthalene



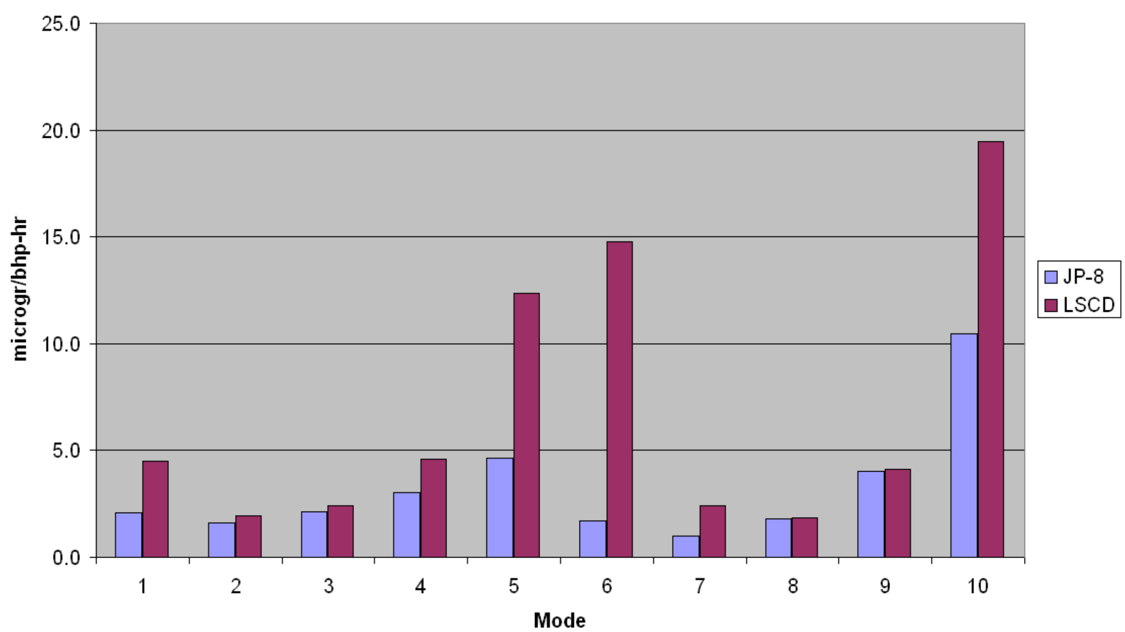

PAH-4
Acenaphthene
25.0
20.0
15.0
10.0
5.0
0.0
microgr/bhp-hr
1
2
3
4
5
6
7
8
9
10
Mode
JP-8
LSCD

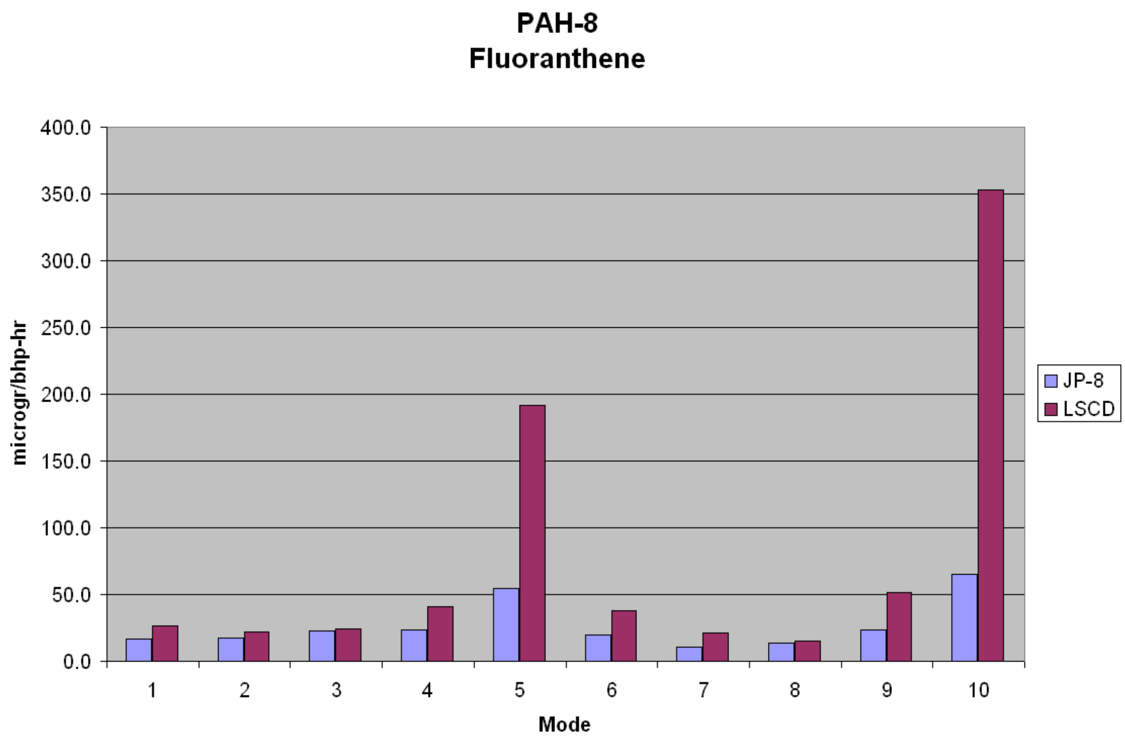

PAH-5
Fluorene
25.0
20.0
15.0
10.0
5.0
0.0
microgr/bhp-hr
1
2
3
4
5
6
7
8
9
10
Mode
JP-8
LSCD

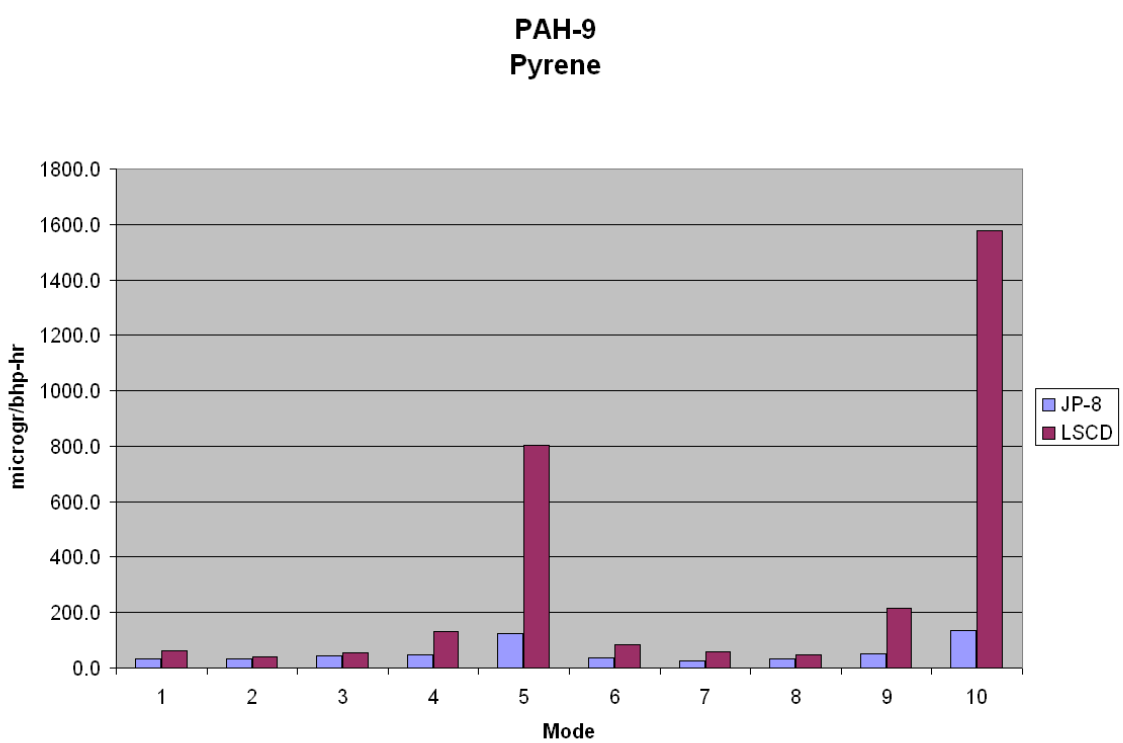
**PAH-6**
**Phenanthrene**

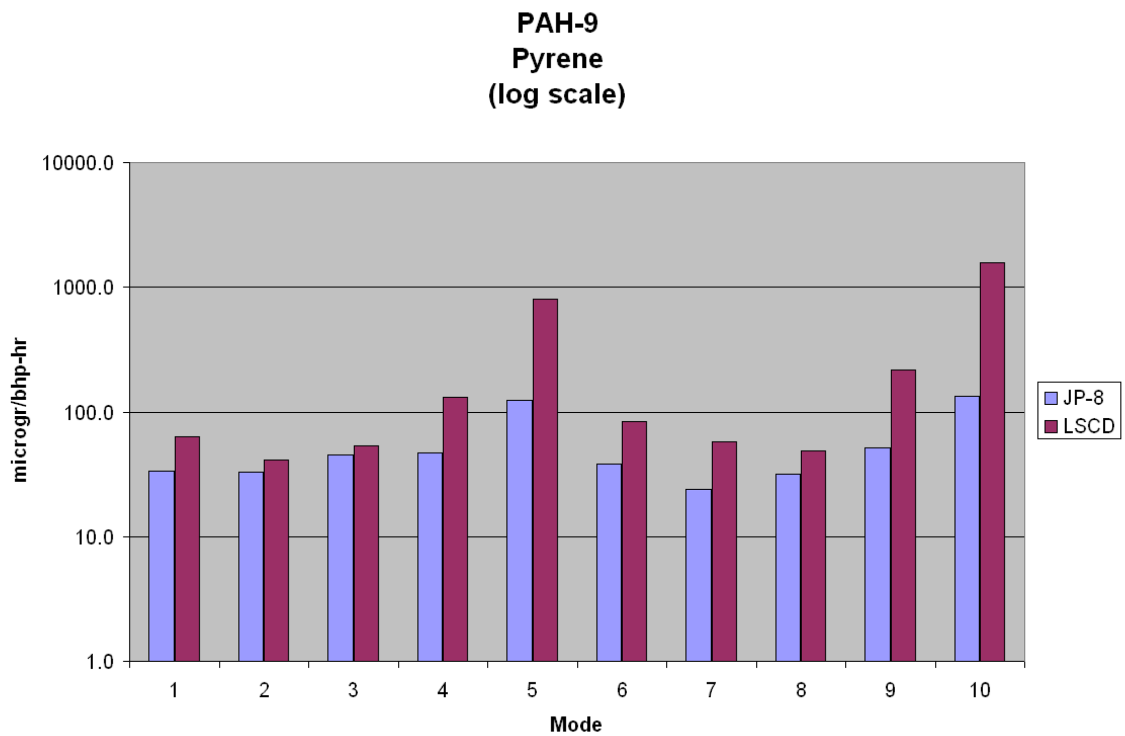


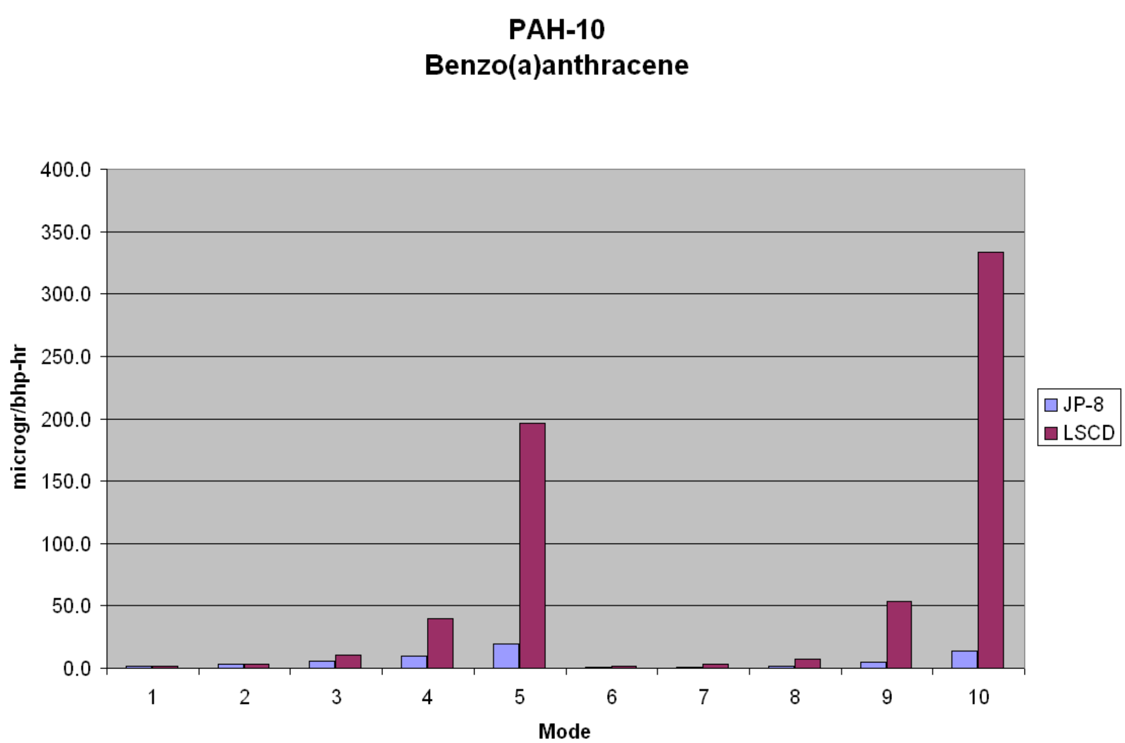

**PAH-7**
**Anthracene**

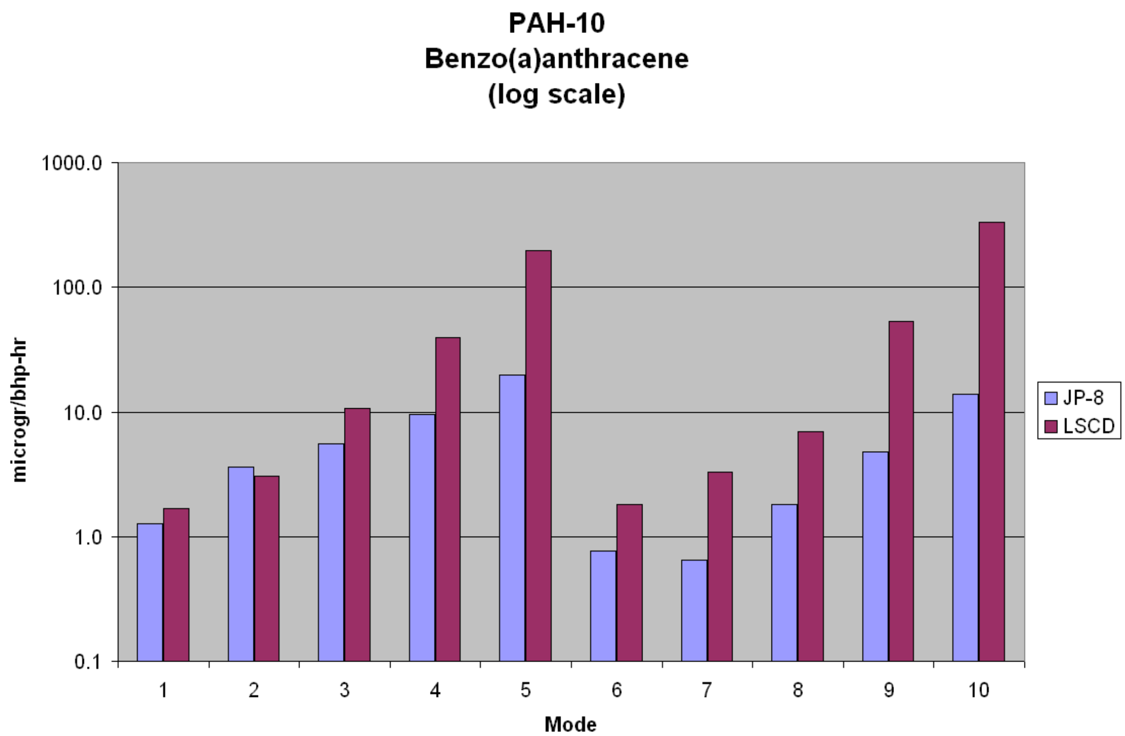


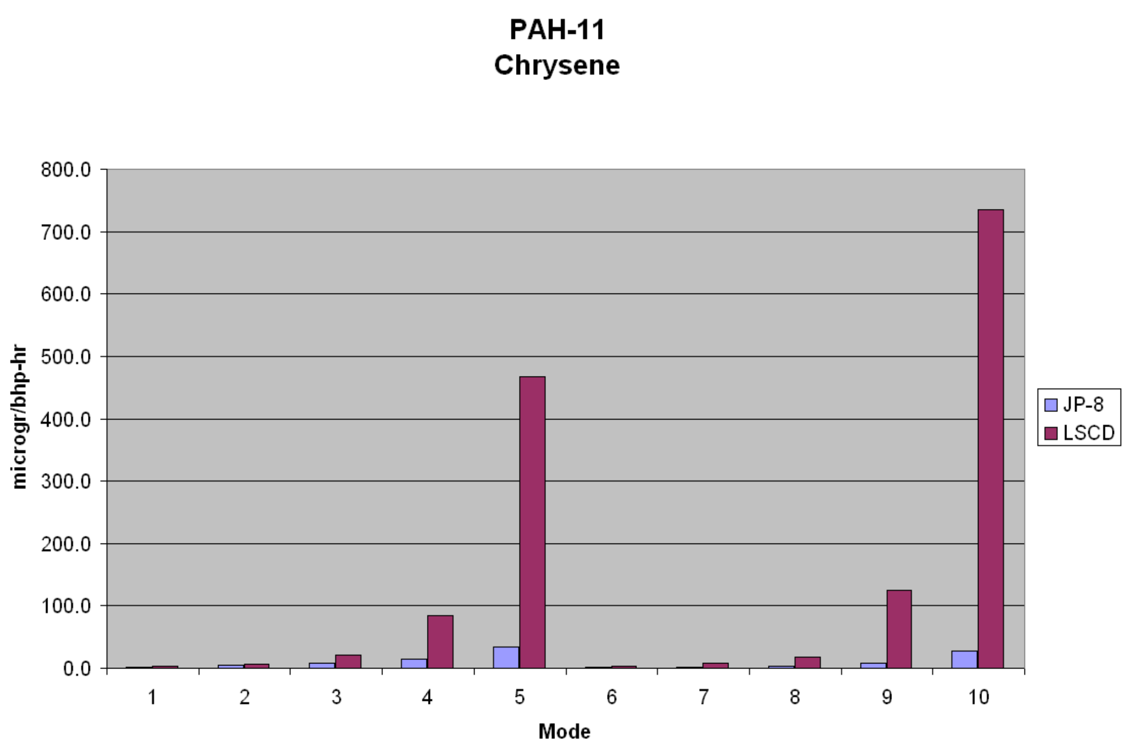

PAH-8
Fluoranthene
microgr/bhp-hr
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
1
2
3
4
5
6
7
8
9
10
Mode
JP-8
LSCD


PAH-9
Pyrene
microgr/bhp-hr
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
1
2
3
4
5
6
7
8
9
10
Mode
JP-8
LSCD

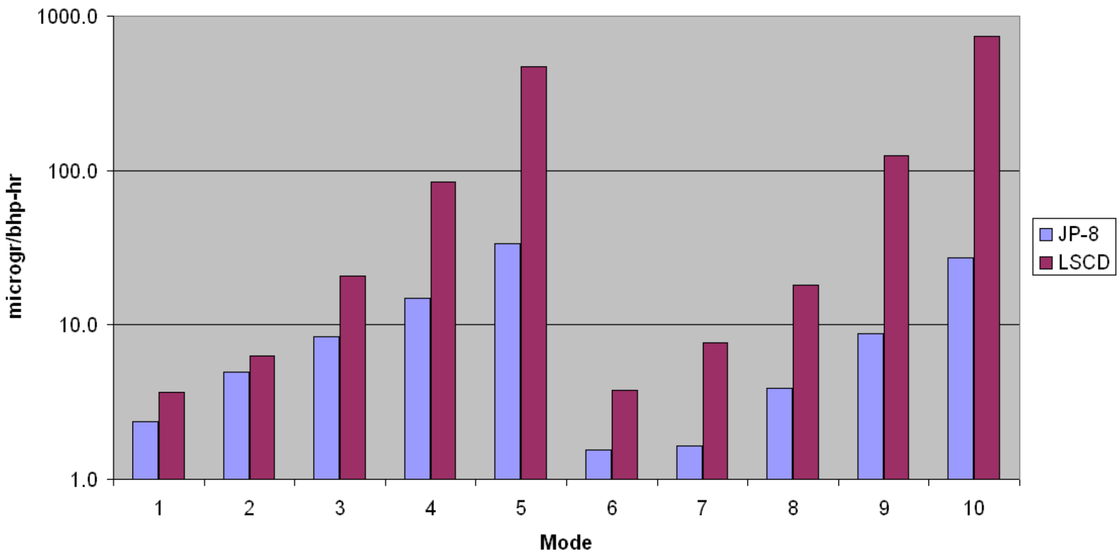

PAH-9
Pyrene
(log scale)
10000.0
1000.0
100.0
10.0
1.0
microgr/bhp-hr
1
2
3
4
5
6
7
8
9
10
Mode
JP-8
LSCD


PAH-10
Benzo(a)anthracene
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
microgr/bhp-hr
1
2
3
4
5
6
7
8
9
10
Mode
JP-8
LSCD

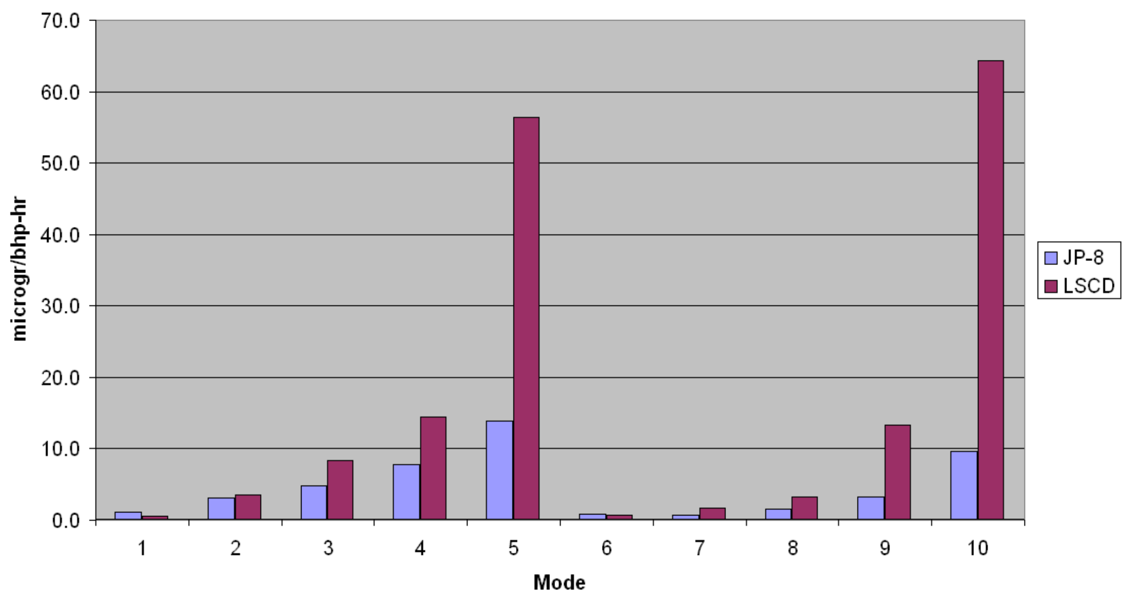

PAH-10
Benzo(a)anthracene
(log scale)
1000.0
100.0
10.0
1.0
0.1
microgr/bhp-hr
1
2
3
4
5
6
7
8
9
10
Mode
JP-8
LSCD


PAH-11
Chrysene
800.0
700.0
600.0
500.0
400.0
300.0
200.0
100.0
0.0
microgr/bhp-hr
1
2
3
4
5
6
7
8
9
10
Mode
JP-8
LSCD

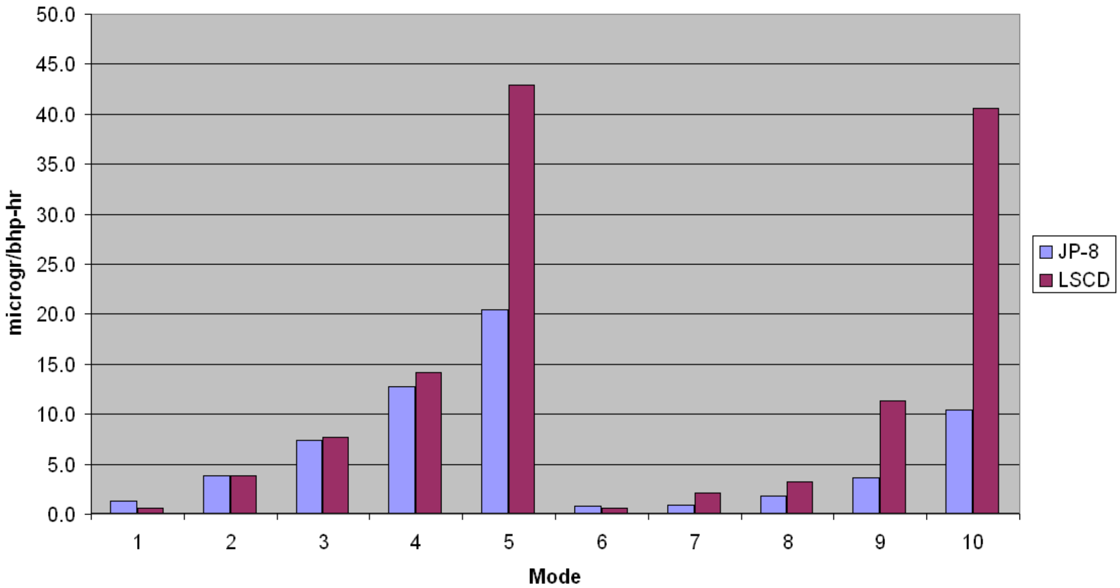
## PAH-11
## Chrysene
## (log scale)



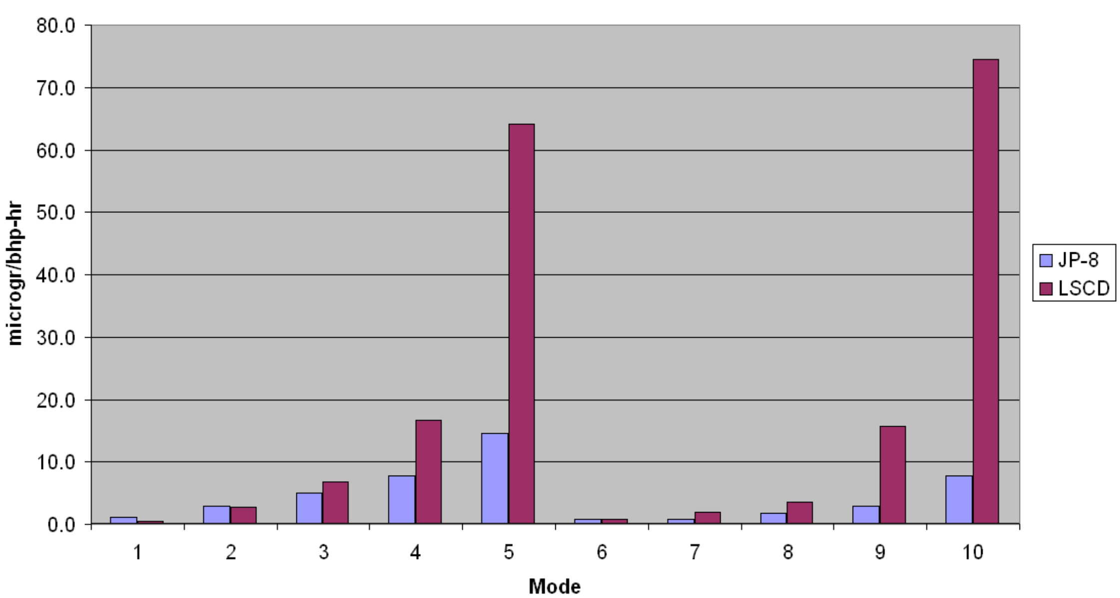

## PAH-12
## Benzo(b)fluoranthene



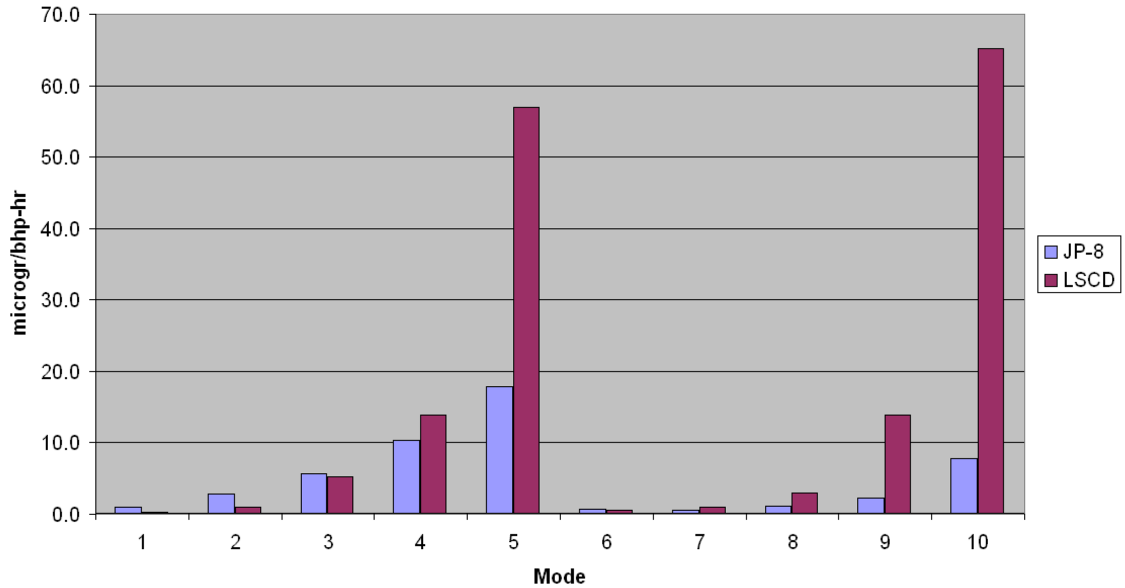
## PAH-13
## Benzo(k)fluoranthene



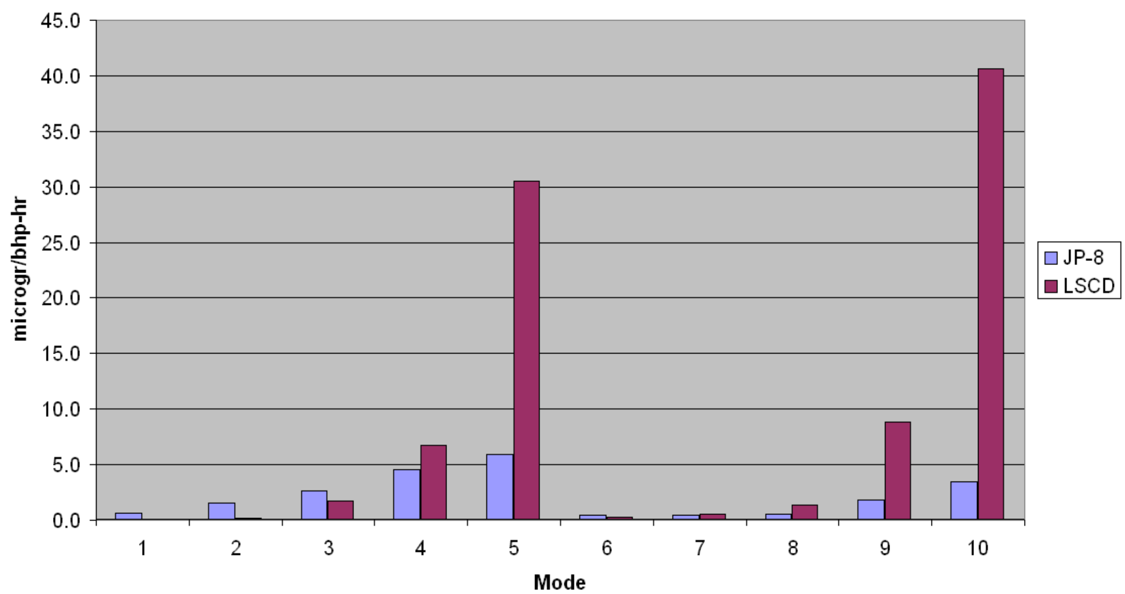

## PAH-14
## Benzo(e)pyrene



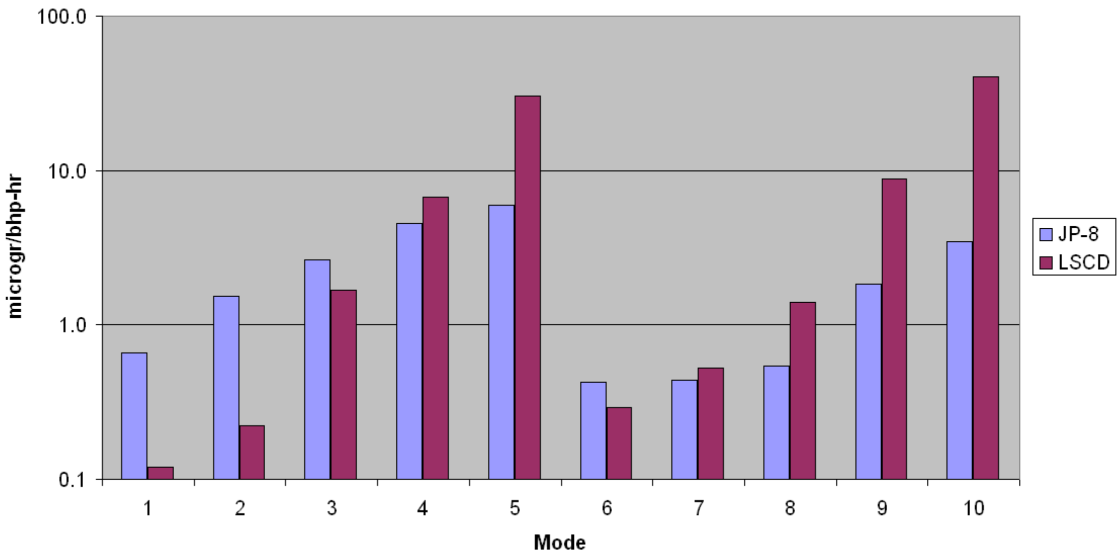
**PAH-15**
**Benzo(a)pyrene**



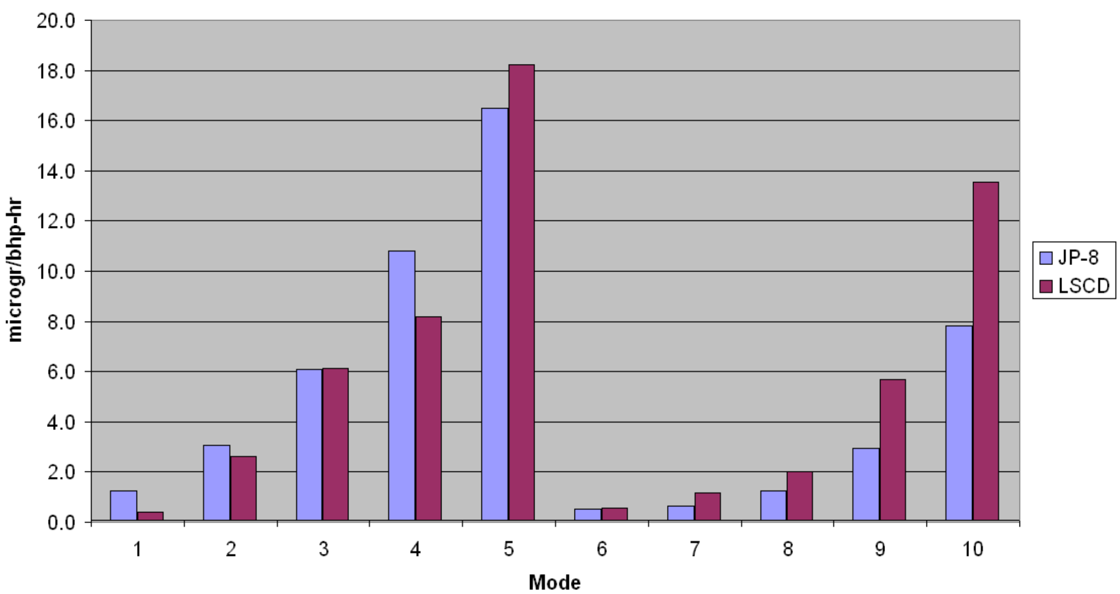

**PAH-16**
**Perylene**



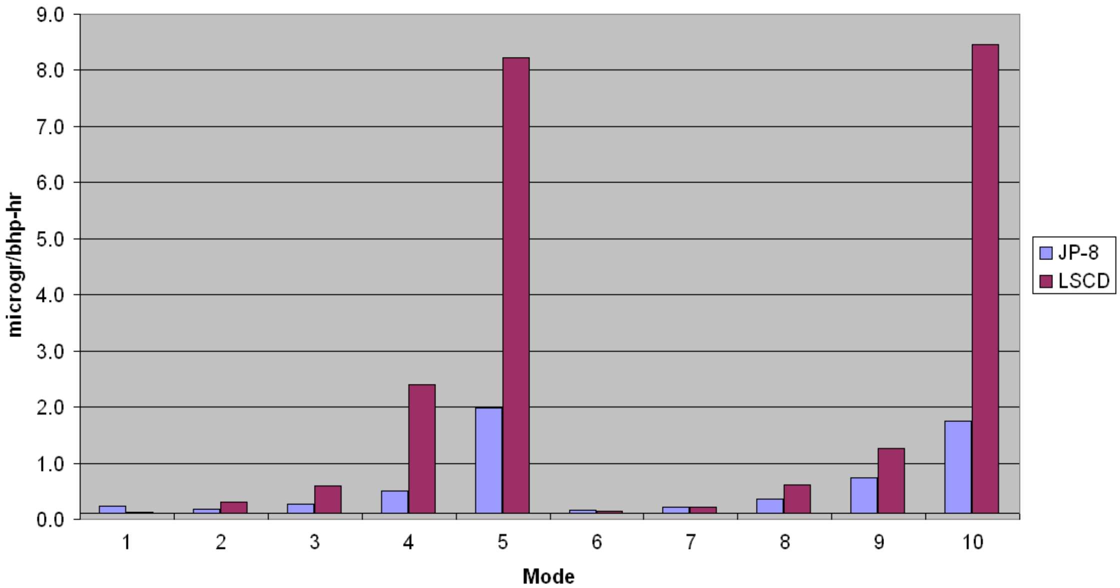
**PAH-16**
**Perylene**
**(log scale)**




**PAH-17**
**Indeno(1,2,3-cd)pyrene**



## PAH-18
## Dibenzo(a,h)anthracene




## PAH-19
## Benzo(g,h,i)perylene