

EMISSIONS FROM A 6.5L HMMVV 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)

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December 2004

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**Edwin C. Owens, Director
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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 PM_{2.5} 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 NO_x and particulate matter.

FOREWARD/ACKNOWLEDGMENTS

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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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- C. 11-Mode Steady-State Emission Results from 6.5L GM Heavy-Duty Diesel Engine using JP-8 and LSCD
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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
NO _x	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 , NO _x , 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 , NO _x , 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 , NO _x , 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, NO_x 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 °C	D86	171-204	189.7
10% Point, °C	D86	204-238	223.0
50% Point, °C	D86	243-282	259.7
90% Point, °C	D86	293-332	309.2
EP, °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, °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, NO_x 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	CO ₂	Non-Dispersive Infrared Analyzer
Oxides of Nitrogen	NO _x	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 NO_x 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 NO_x 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 NO_x level that would be produced by LSCD at the same power achieved on JP-8. Figure 4 shows the estimated LSCD NO_x 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, NO_x, 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:

- NO_x-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 NO_x emissions and substantially lower PM emissions compared to LSCD,

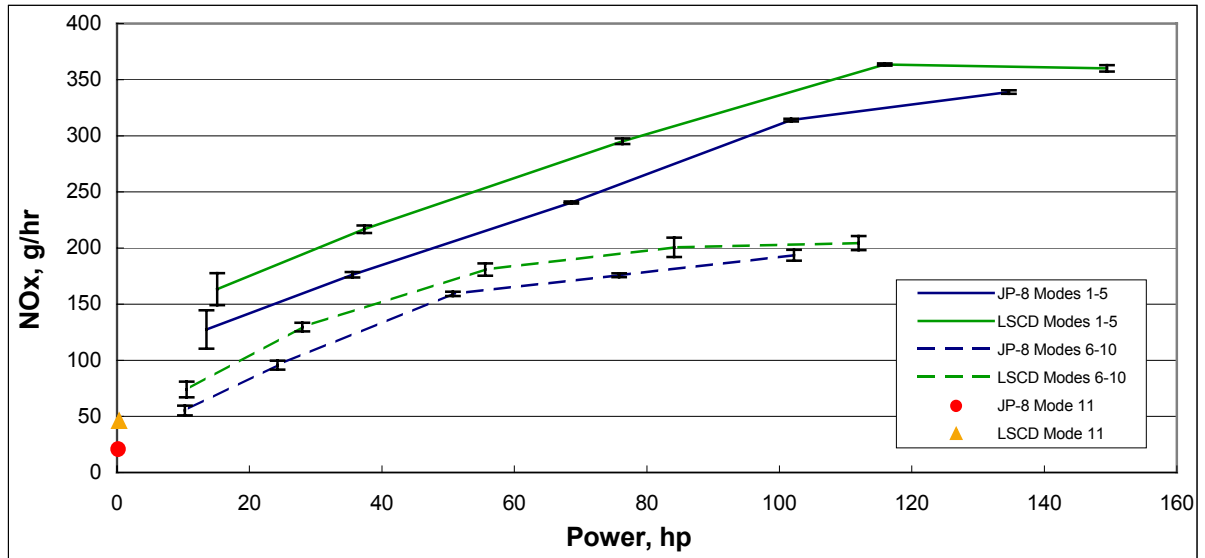


FIGURE 2. AVERAGE NO_x EMISSION RATES FROM GM 6.5L ENGINE FOR 11 STEADY-STATE MODES USING LSCD AND JP-8 (STRAIGHT-LINE CONNECTOR)

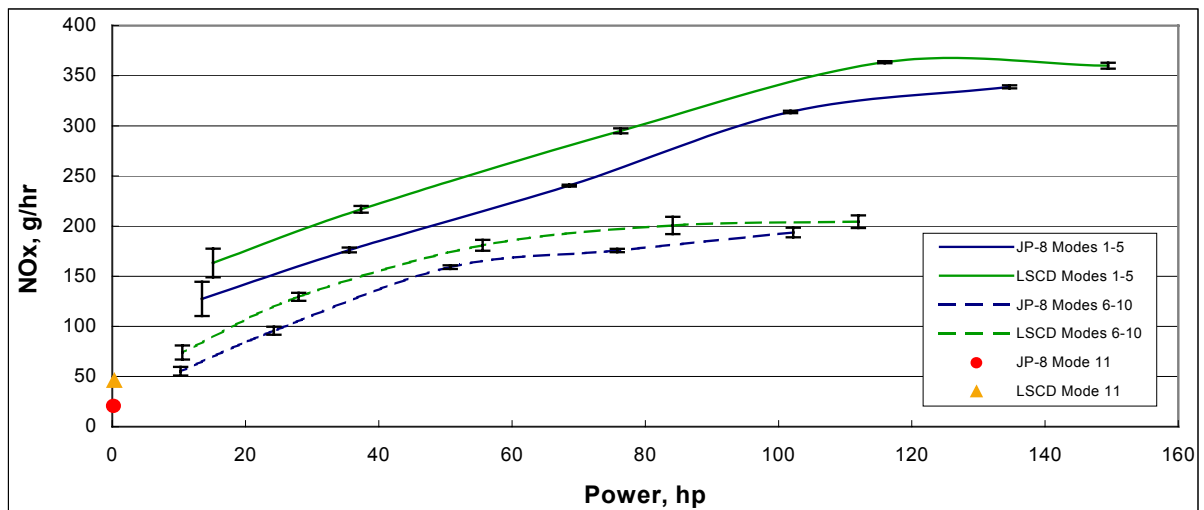


FIGURE 3. AVERAGE NO_x EMISSION RATES FROM GM 6.5L ENGINE FOR 11 STEADY-STATE MODES USING LSCD AND JP-8 (SMOOTHED-LINE CONNECTOR)

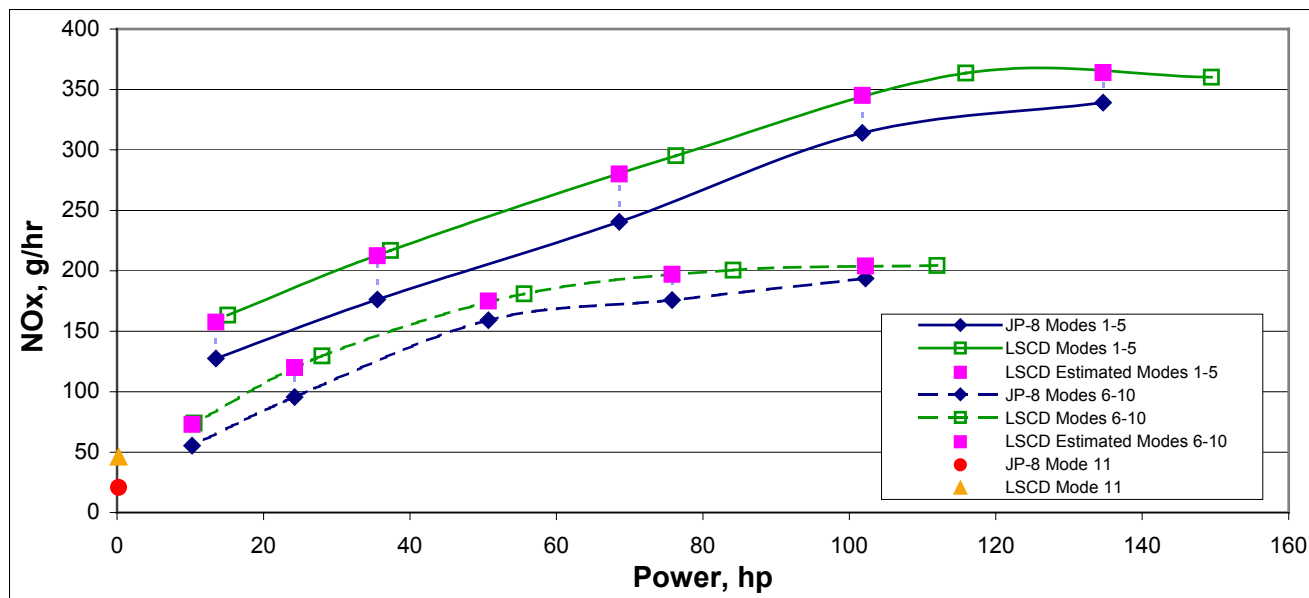


FIGURE 4. AVERAGE AND ESTIMATED NO_x EMISSION RATES FROM GM 6.5L ENGINE FOR 11 STEADY-STATE MODES USING LSCD AND JP-8 (SMOOTHED-LINE CONNECTOR)

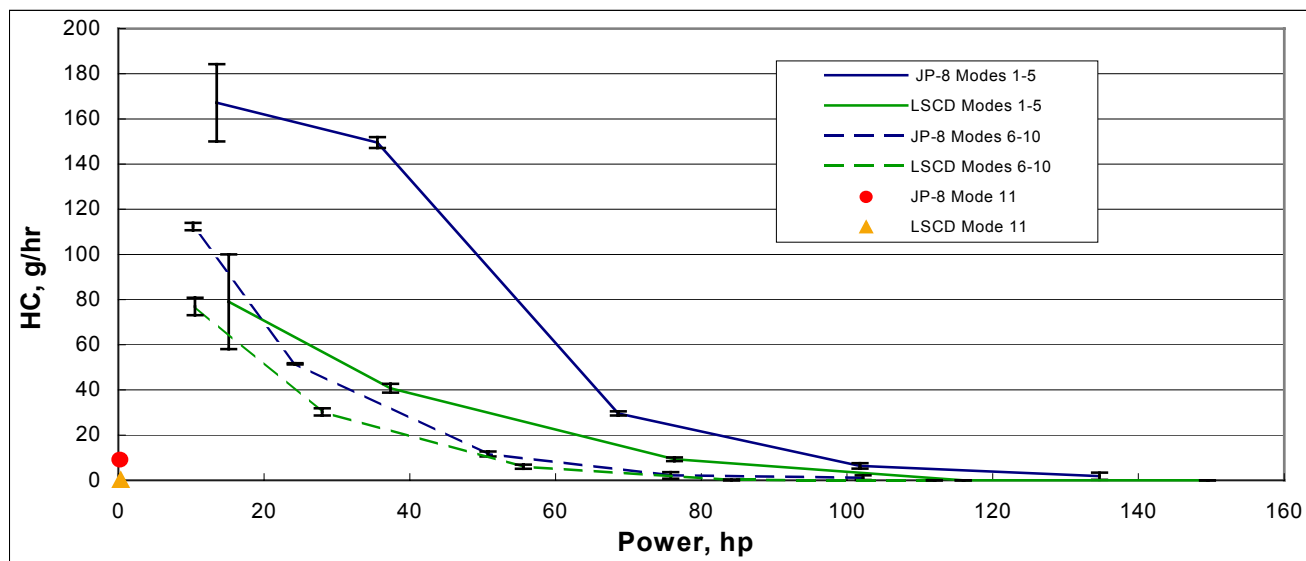


FIGURE 5. AVERAGE HC EMISSION RATES FROM GM 6.5L ENGINE FOR 11 STEADY-STATE MODES USING LSCD AND JP-8 (STRAIGHT-LINE-CONNECTOR)

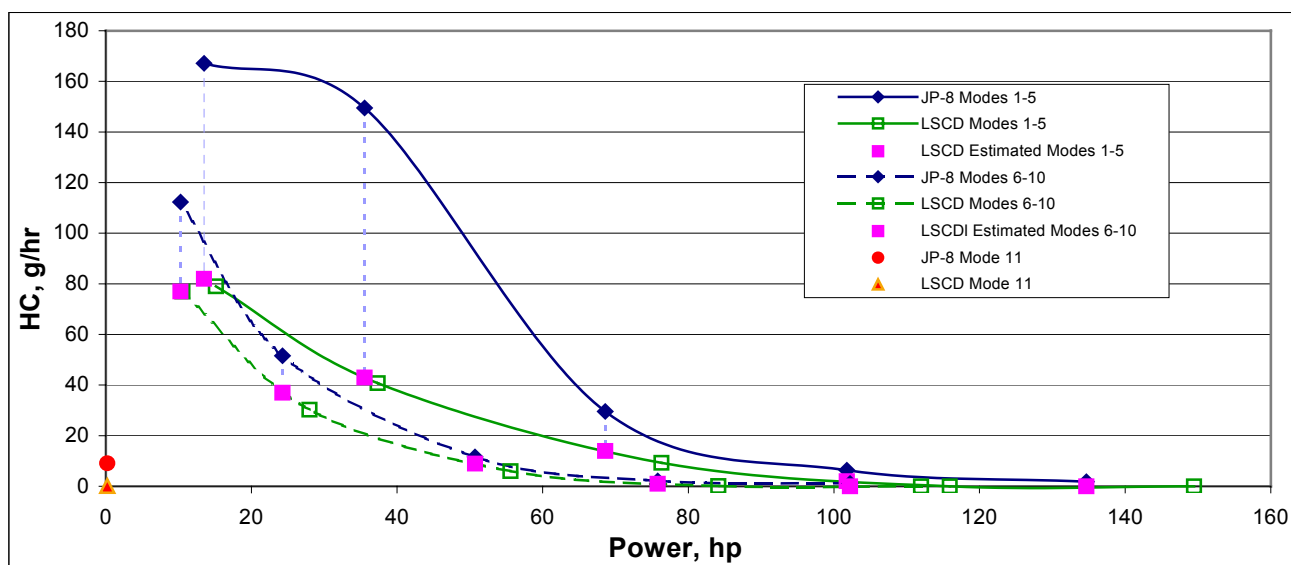


FIGURE 6. AVERAGE AND ESTIMATED HC EMISSION RATES FROM GM 6.5L ENGINE FOR 11 STEADY-STATE MODES USING LSCD AND JP-8 (SMOOTHED-LINE CONNECTOR)

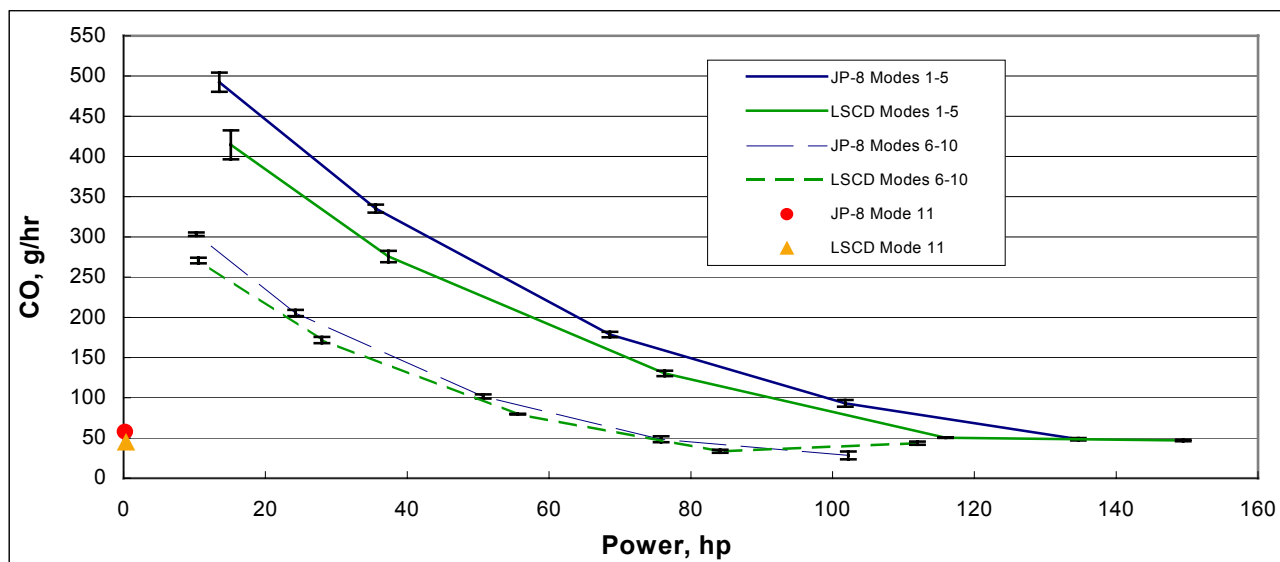


FIGURE 7. AVERAGE CO EMISSION RATES FROM GM 6.5L ENGINE FOR 11 STEADY-STATE MODES USING LSCD AND JP-8 (STRAIGHT-LINE CONNECTOR)

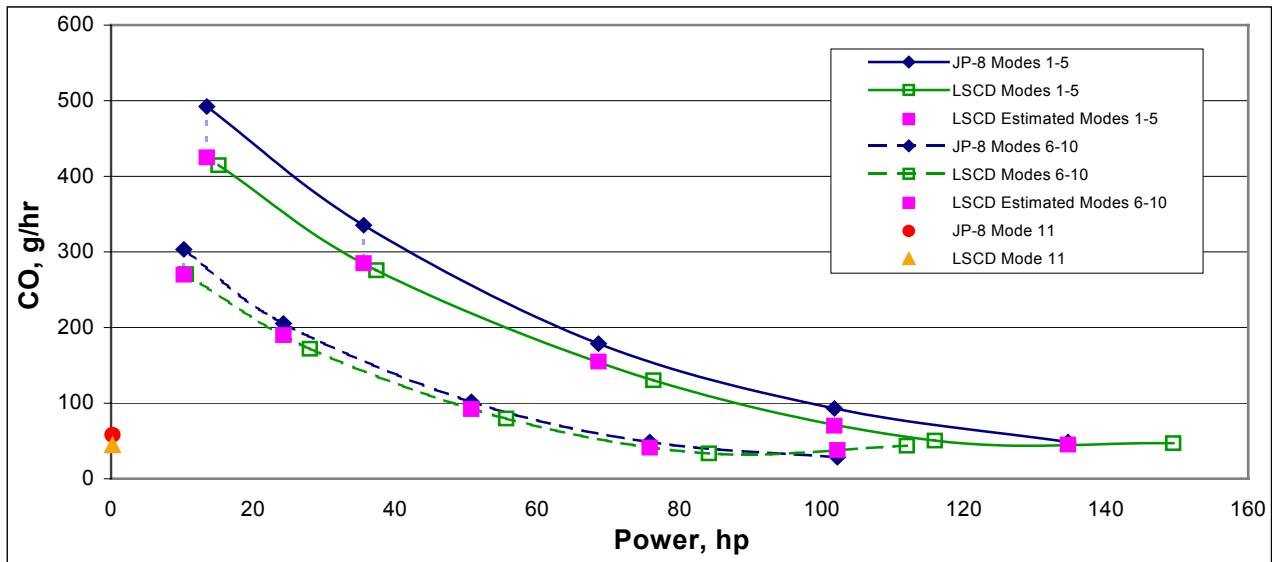


FIGURE 8. AVERAGE AND ESTIMATED CO EMISSION RATES FROM GM 6.5L ENGINE FOR 11 STEADY-STATE MODES USING LSCD AND JP-8 (SMOOTHED-LINE CONNECTOR)

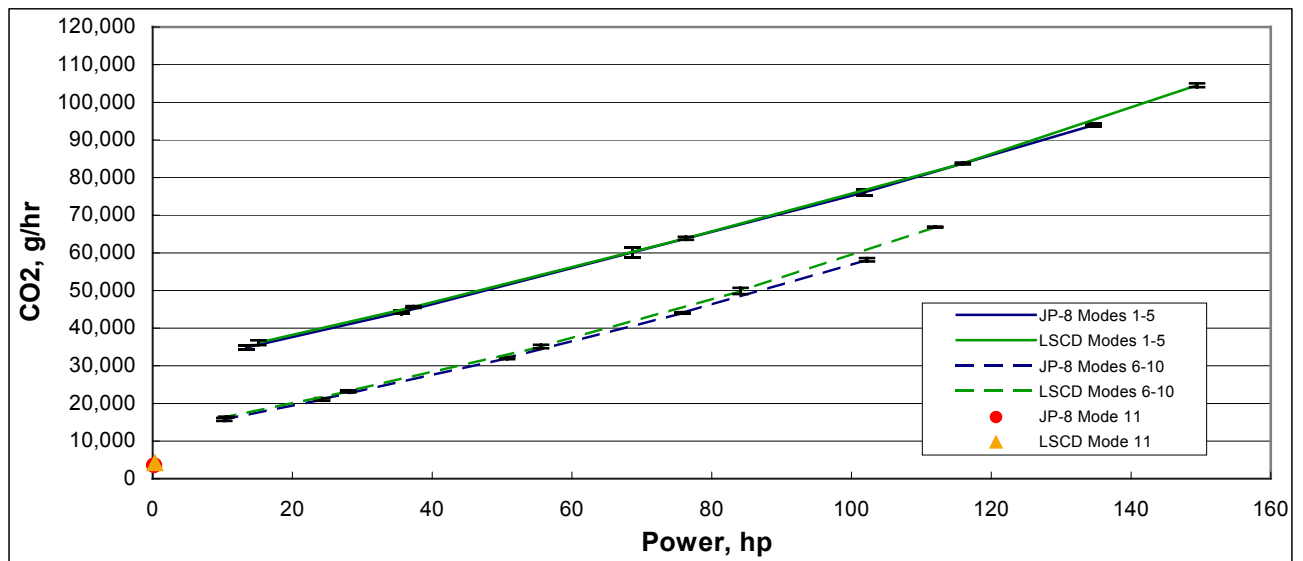


FIGURE 9. AVERAGE CO₂ EMISSION RATES FROM GM 6.5L ENGINE FOR 11 STEADY-STATE MODES USING LSCD AND JP-8 (STRAIGHT-LINE CONNECTOR)

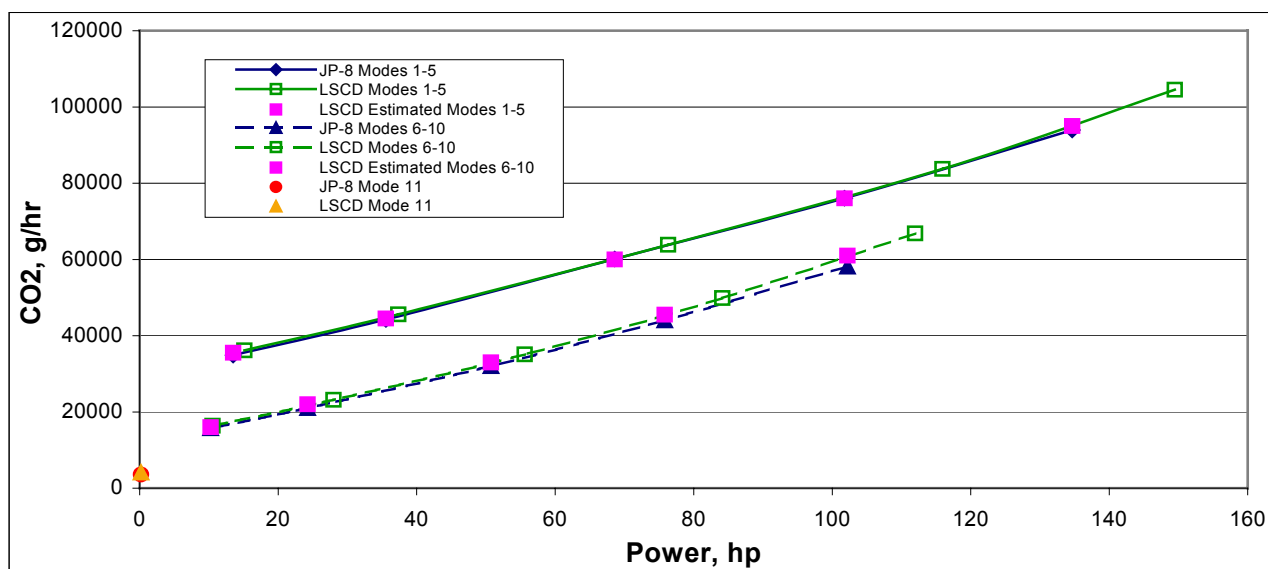


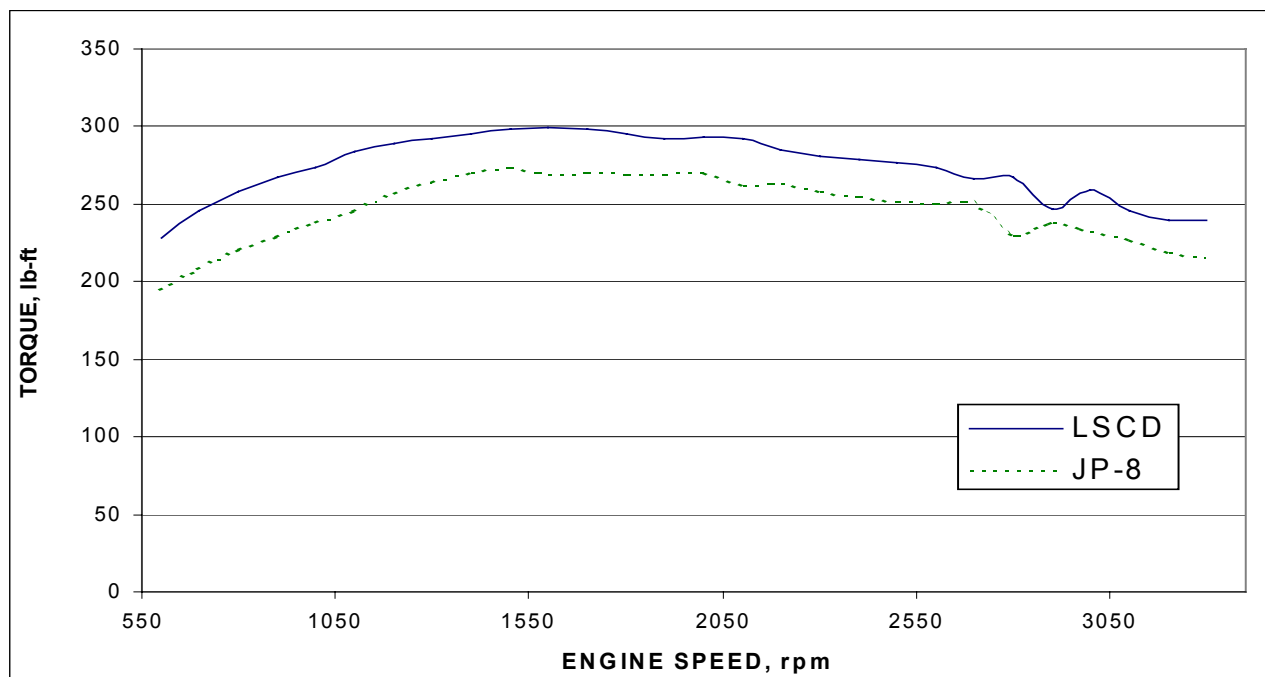
FIGURE 10. AVERAGE AND ESTIMATED CO₂ EMISSION RATES FROM GM 6.5L ENGINE FOR 11 STEADY-STATE MODES USING LSCD AND JP-8 (SMOOTHED-LINE CONNECTOR)

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)					SOF (g/hr)	SOF %	8-Mode Wt. Factor
				HC	CO	CO ₂	NO _x	PM			
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	Mode	Power	Brake-Specific Emission Results (g/hp-hr)					SOF	SOF	8-Mode
ID	Number	hp	HC	CO	CO2	NOx	PM	g/hp-hr	% of PM	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

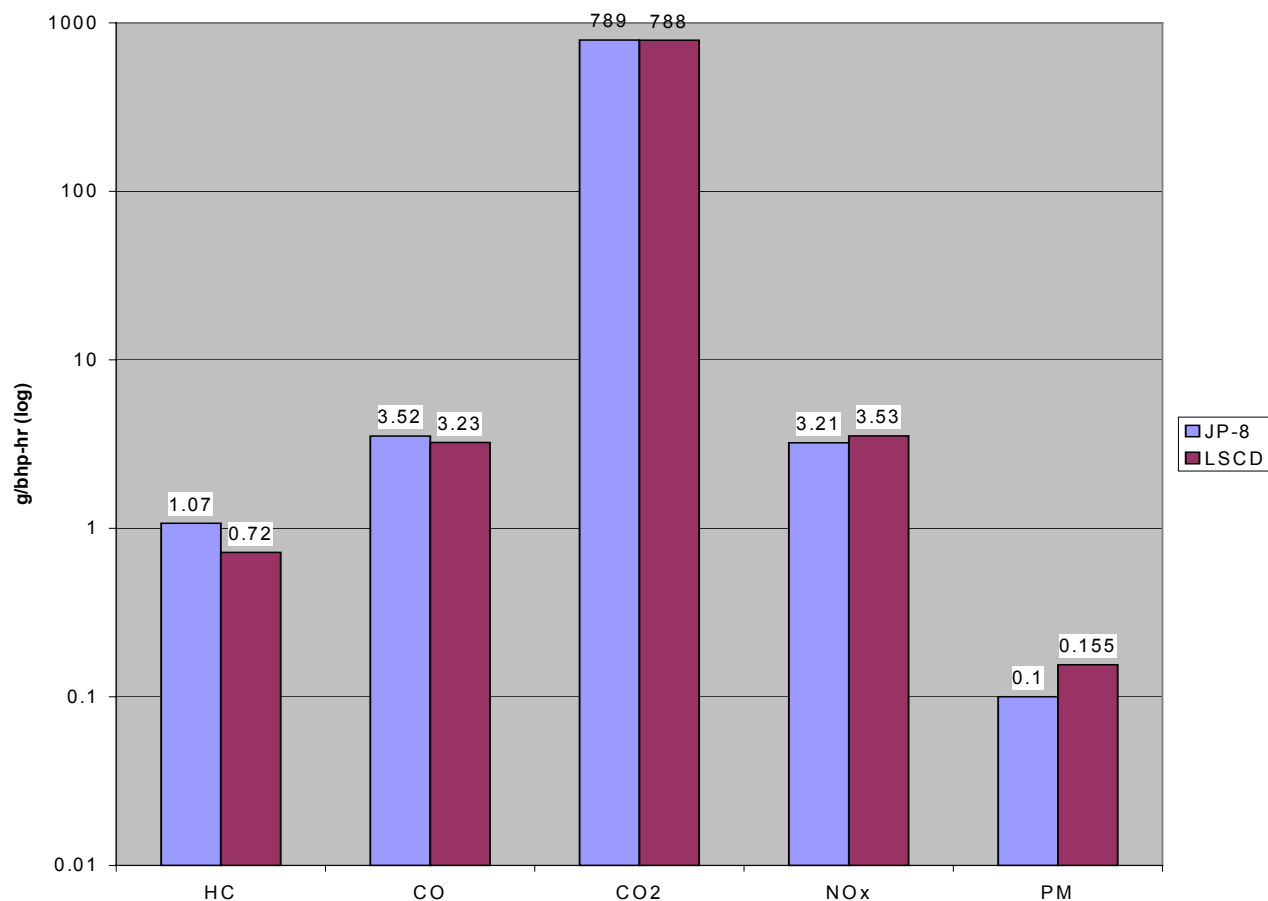


FIGURE 12. EXHAUST EMISSIONS NONROAD TRANSIENT TEST CYCLE (SAT)

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	CO ₂	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.

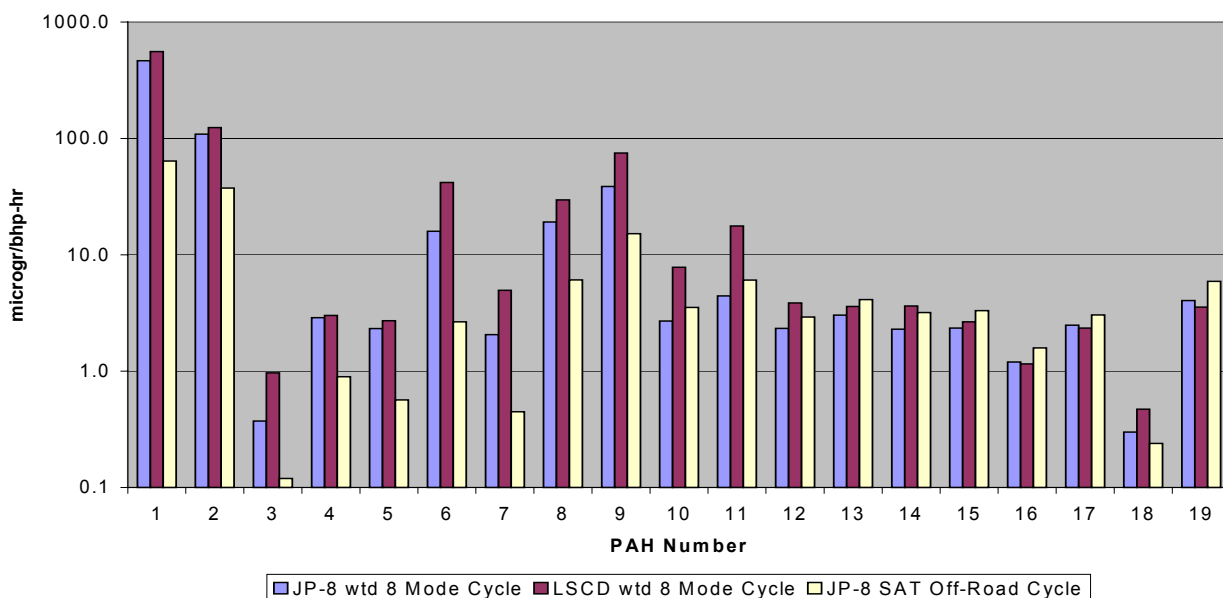


FIGURE 13. PAH's BY TEST CYCLE

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

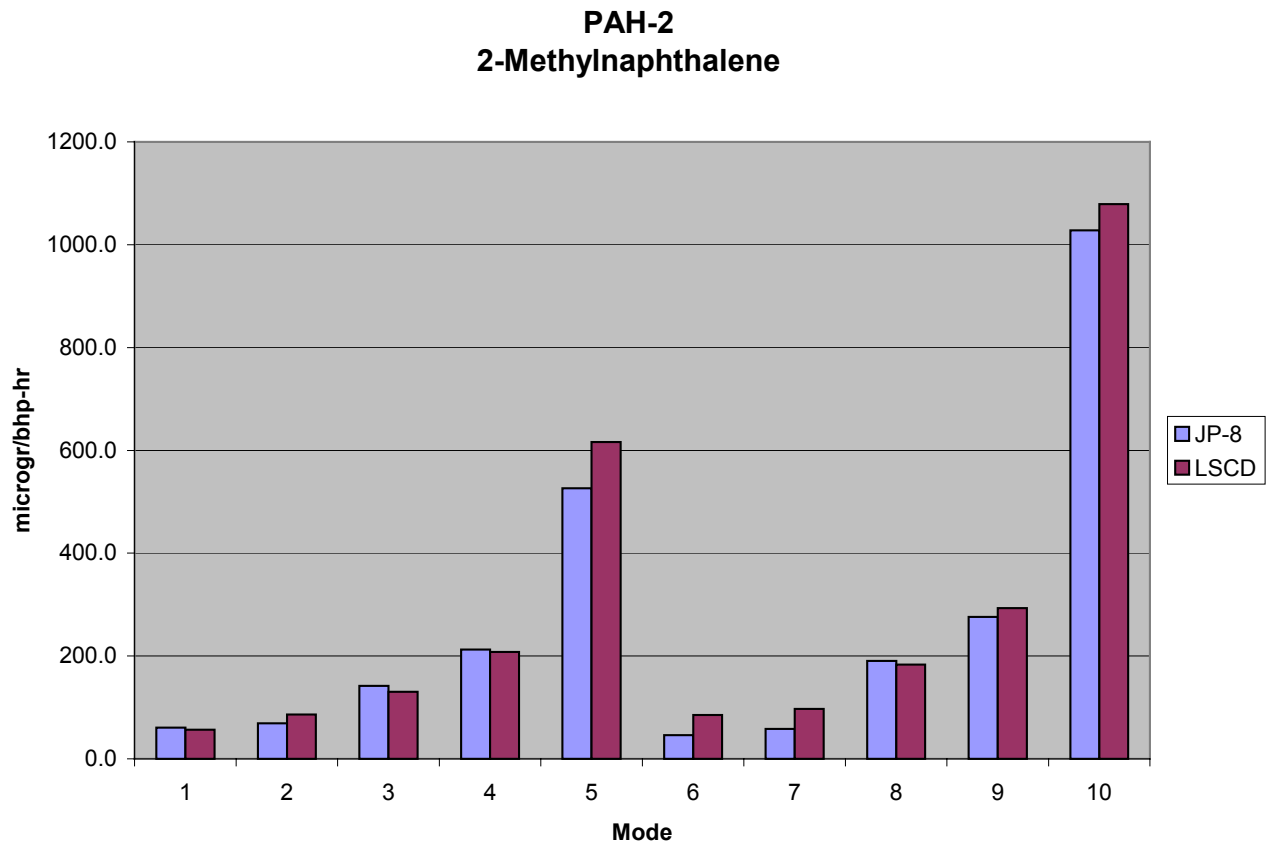


FIGURE 14. PAH-2

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 NO_x 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 NO_x 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 Type	Fuel ID	Brake Specific Emissions (g/hp-hr)						BSFC lb/hp-hr
		HC	CO	CO ₂	NO _x	PM	SOF	
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

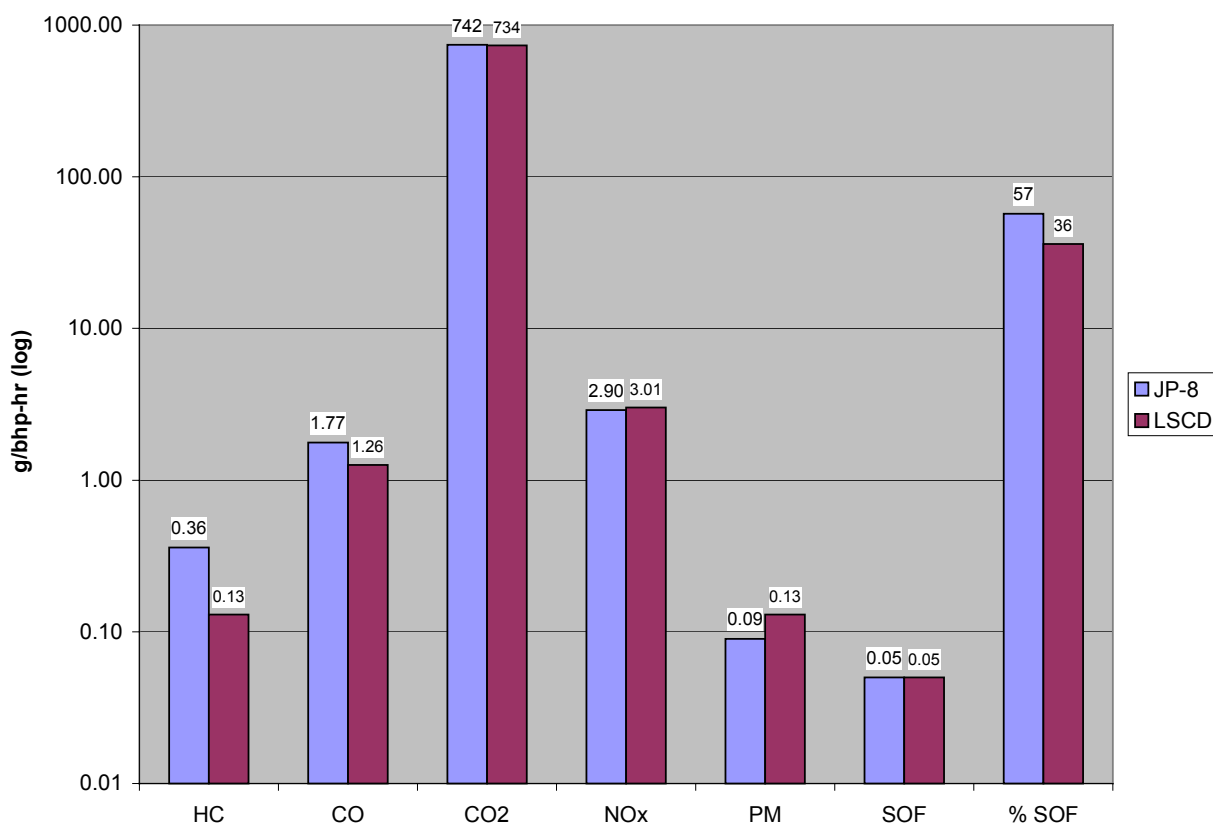


FIGURE 15. WEIGHTED 8-MODE EXHAUST EMISSIONS

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.

PAH-15
Benzo(a)pyrene

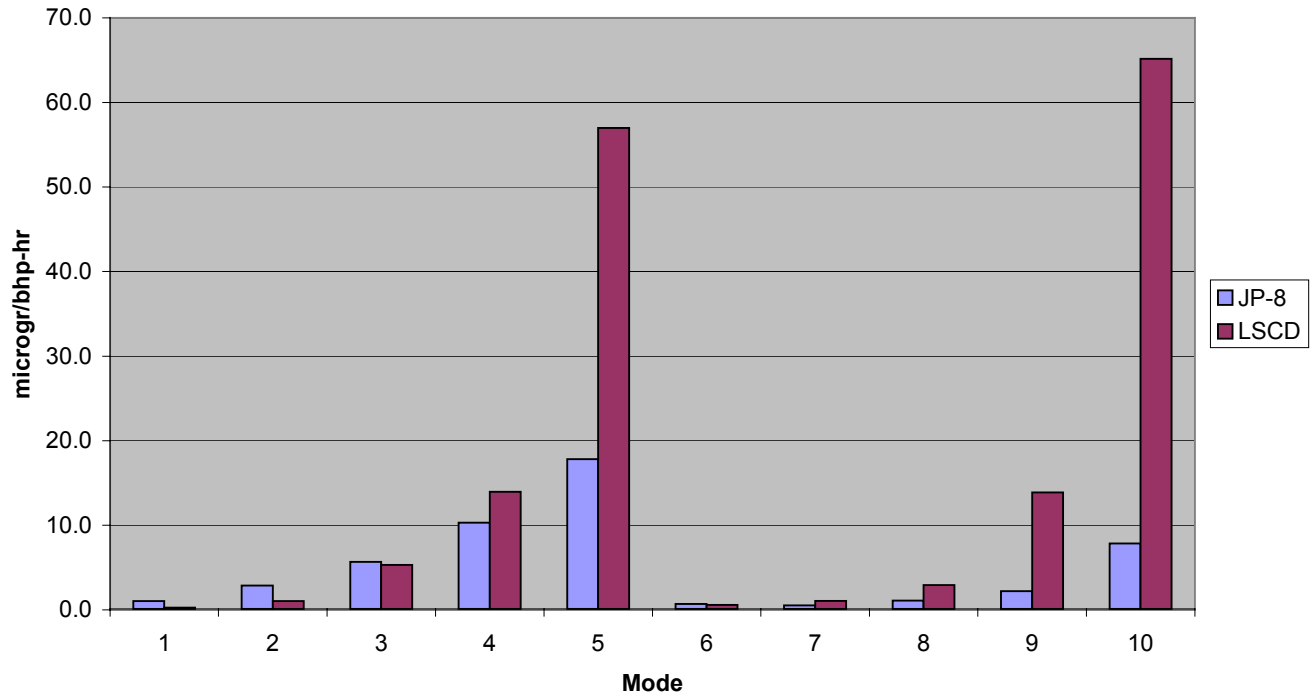


FIGURE 16. BAP EMISSION FROM PARTICULATE MATTER

5.0 REFERENCES

1. 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.
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 (<i>governed</i>)	3900			rpm
9	Low Idle (<i>curb idle</i>)	700			rpm
10	CITT @ rpm (<i>automatic transmission application</i>)	NA	lb-ft @		rpm
11	Cranking Speed	150			rpm
12	Water Outlet Temperature	thermostat	+/-5		°F
13	Pressure Drop Across Intercooler	NA			"H ₂ O
14	Air Temperature After Intercooler	min. NA	max. NA		°F
15	Engine Oil Viscosity (<i>SAE rating</i>)	15W40			
16	Engine Coolant Type (<i>water, %water + %glycol, etc.</i>)	Water + Glycol			
17	Intake and Exhaust Restrictions	Part 86 Transient	Federal Smoke	Part 89 ^a Nonroad	
18	Intake Restriction ^b +/- (1.0 "H ₂ O)			15.3@ Rated	"H ₂ O
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

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APPENDIX D

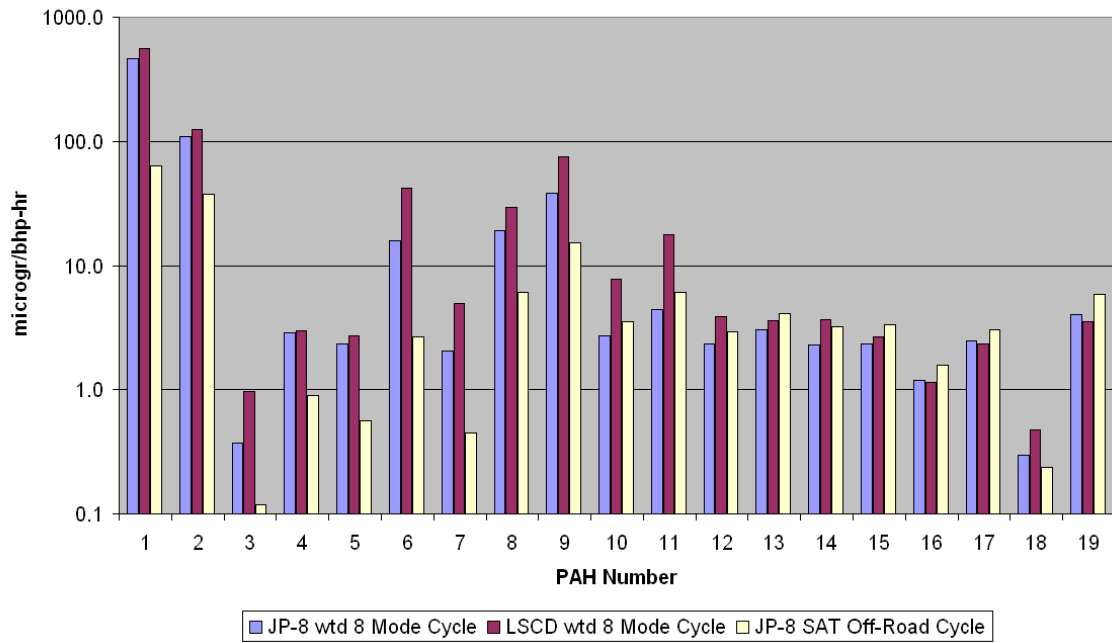
SAT NONROAD TRANSIENT EMISSION RESULTS FROM 6.5L GM HEAVY-DUTY DIESEL ENGINE USING JP-8

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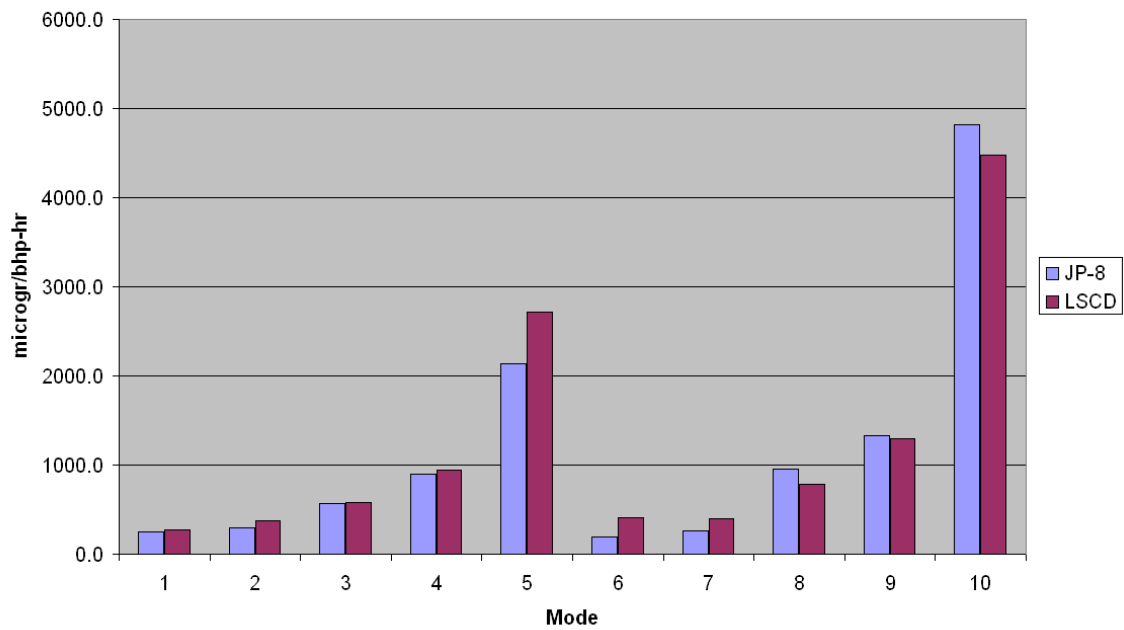
APPENDIX E

BRAKE-SPECIFIC PAH'S

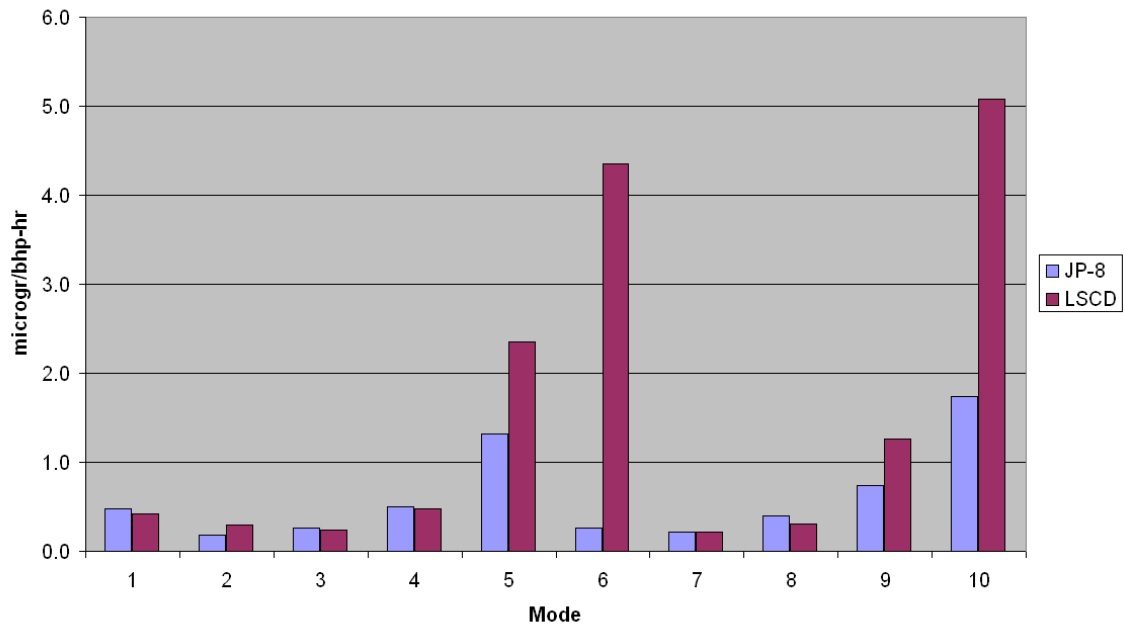
**PAH's by Test Cycle
(log scale)**



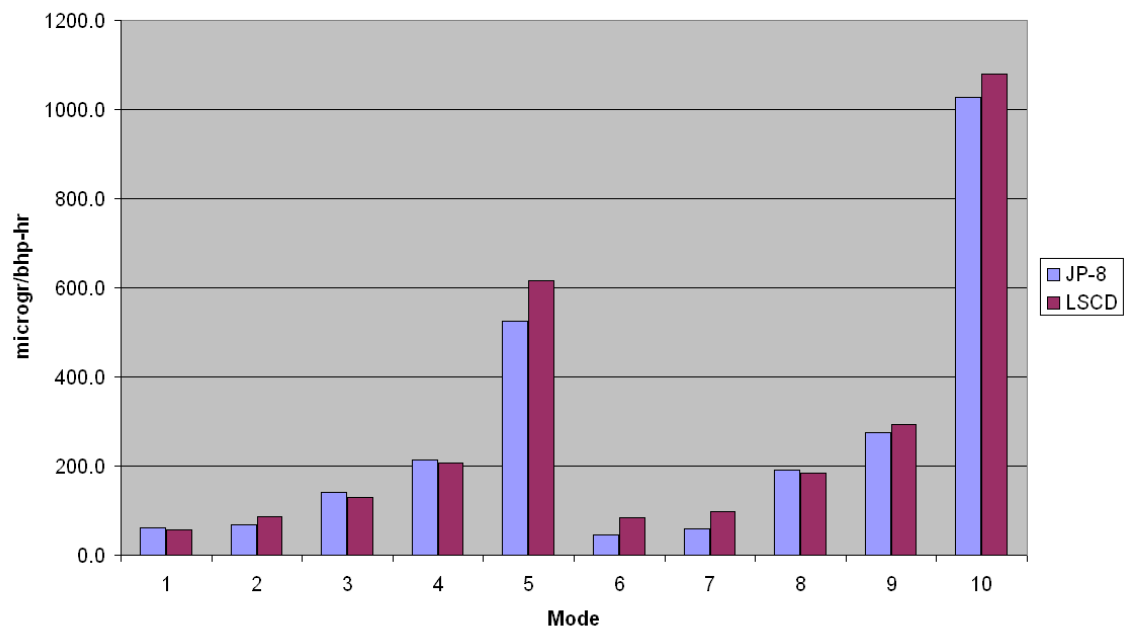
**PAH-1
Naphthalene**



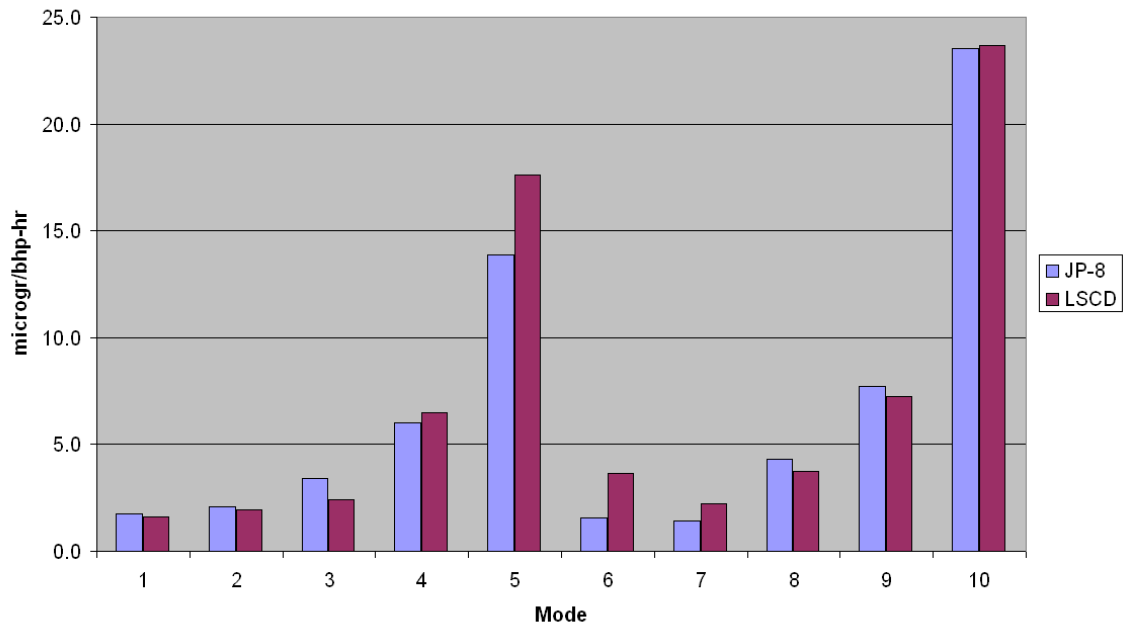
PAH-3
Acenaphthylene



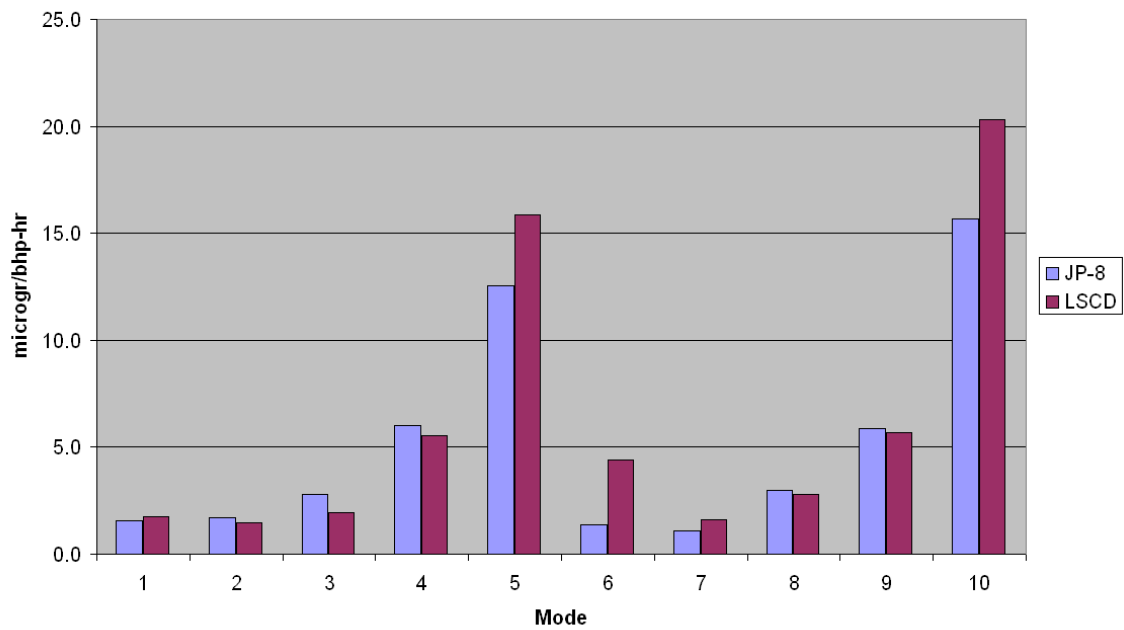
PAH-2
2-Methylnaphthalene



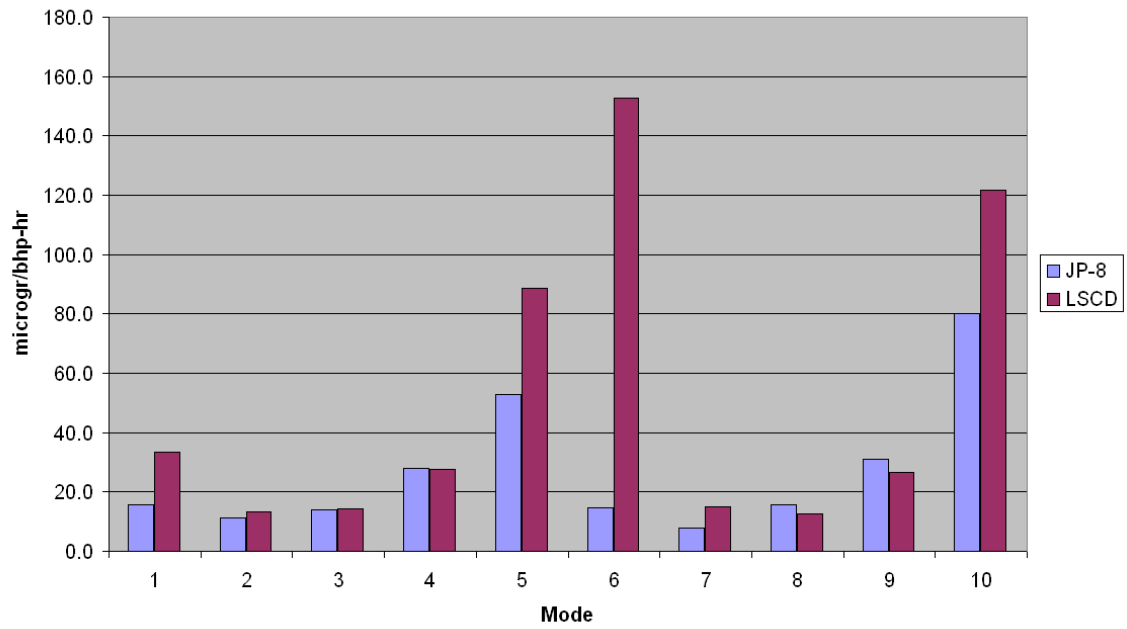
PAH-4
Acenaphthene



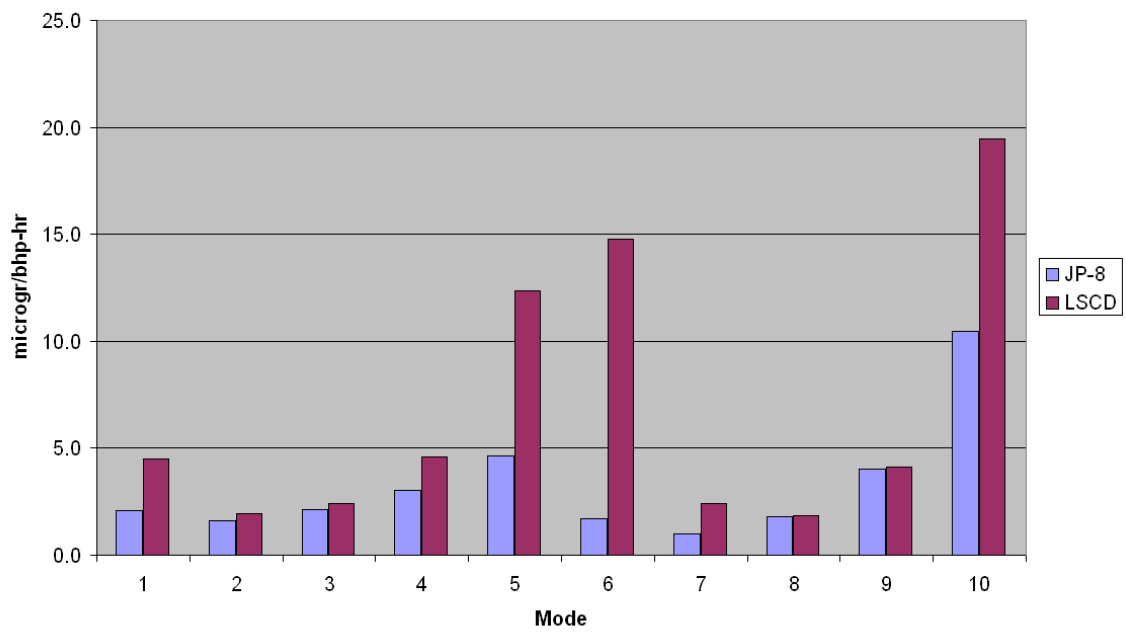
PAH-5
Fluorene



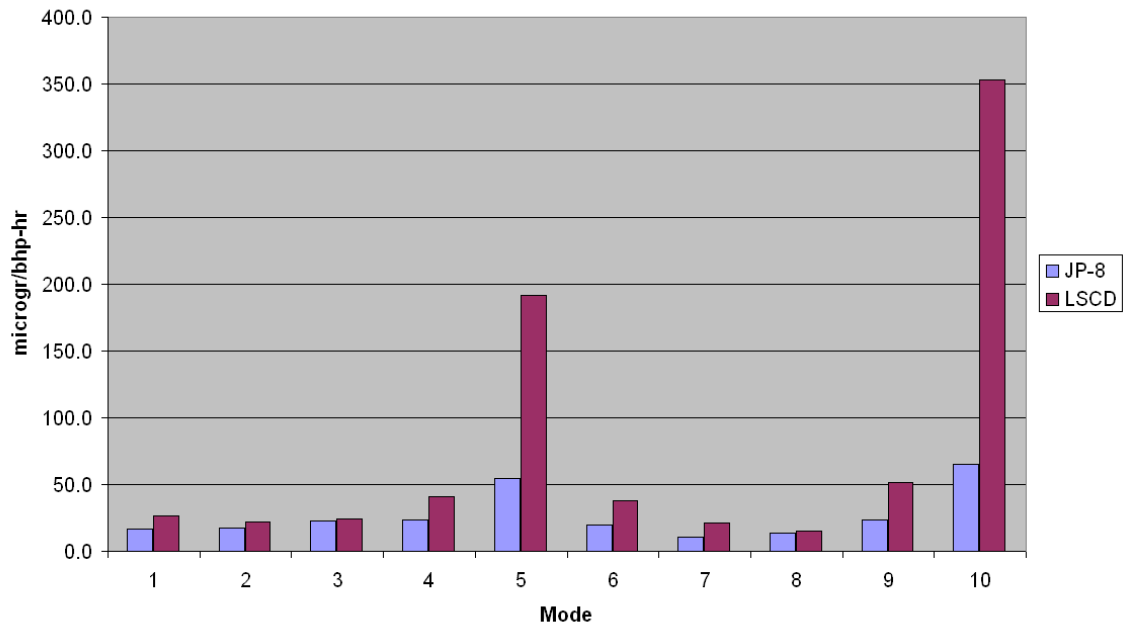
PAH-6
Phenanthrene



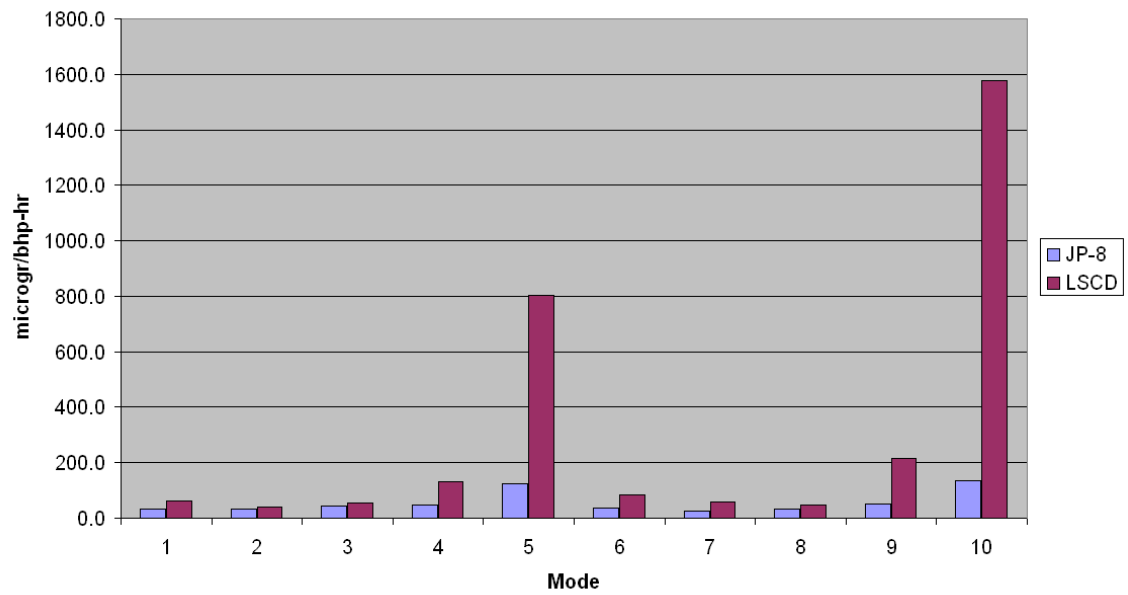
PAH-7
Anthracene



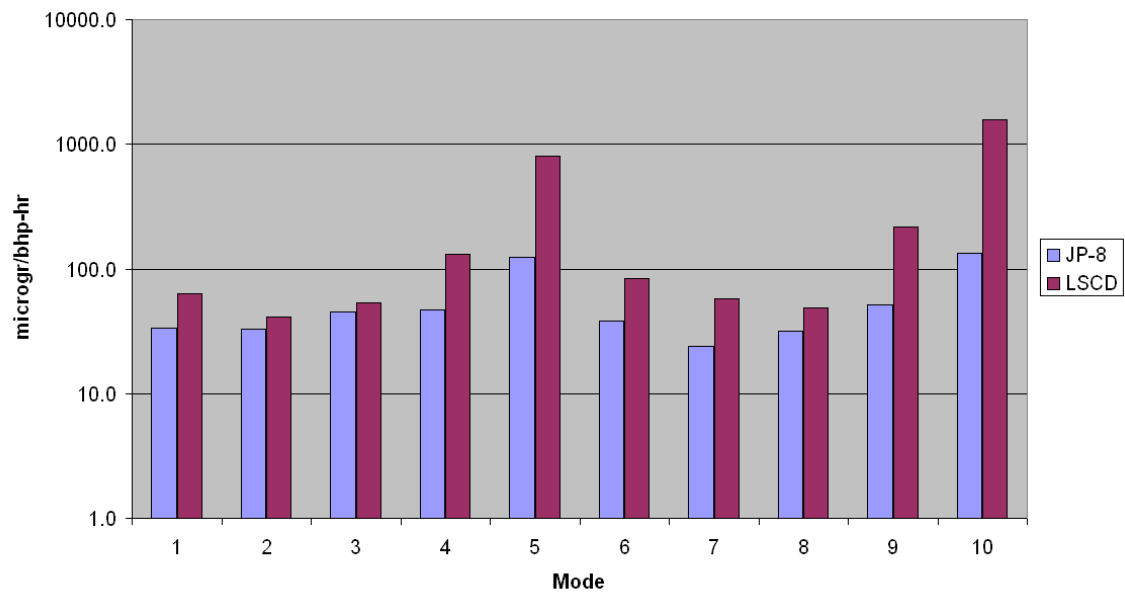
**PAH-8
Fluoranthene**



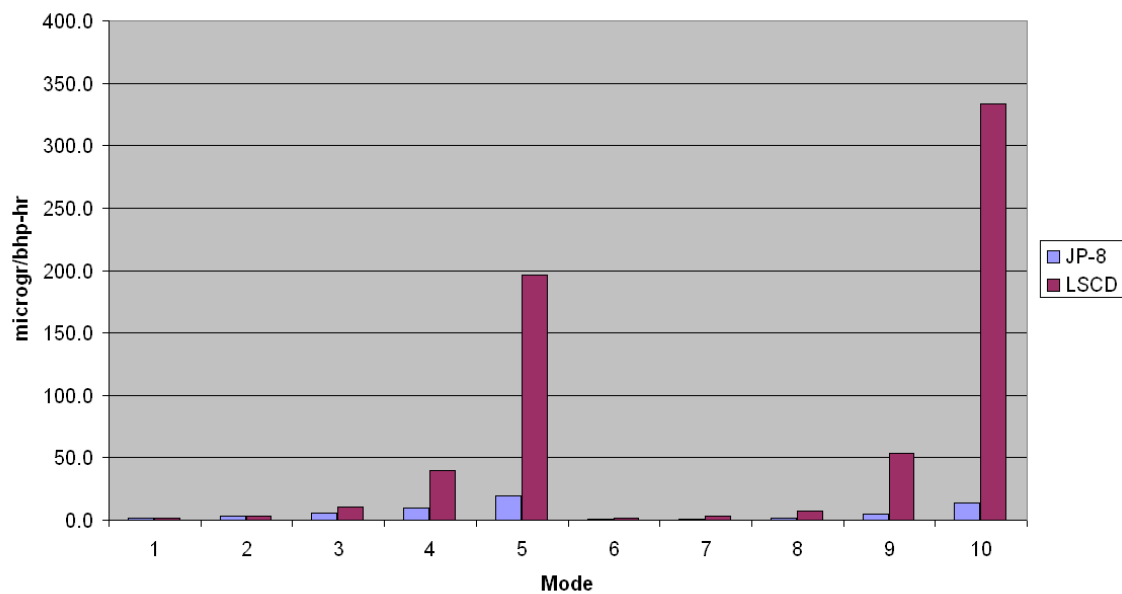
**PAH-9
Pyrene**



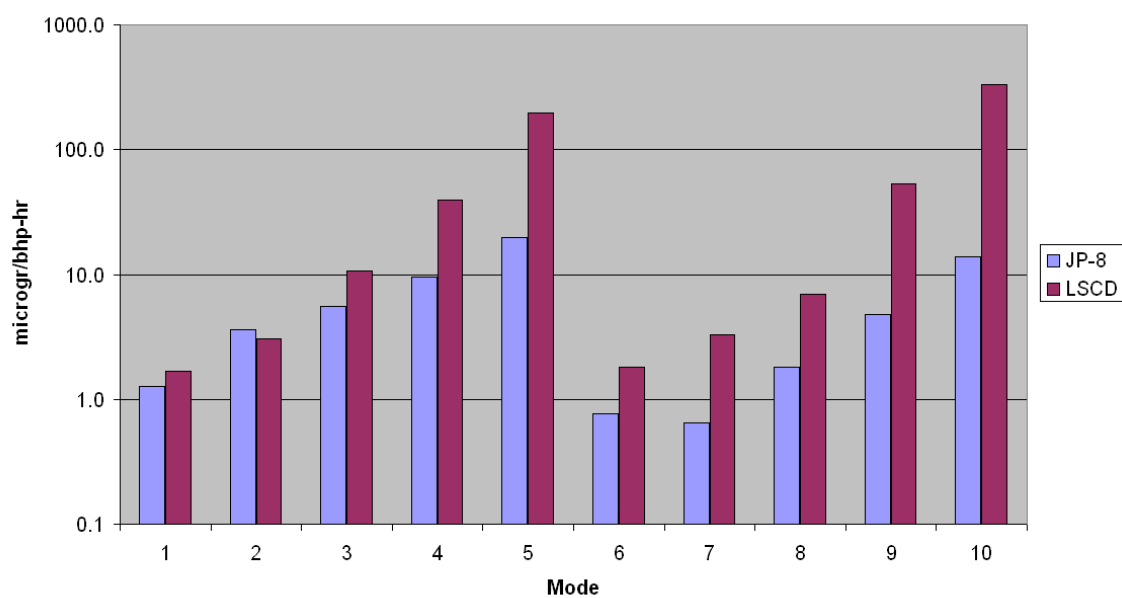
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Pyrene
(log scale)**



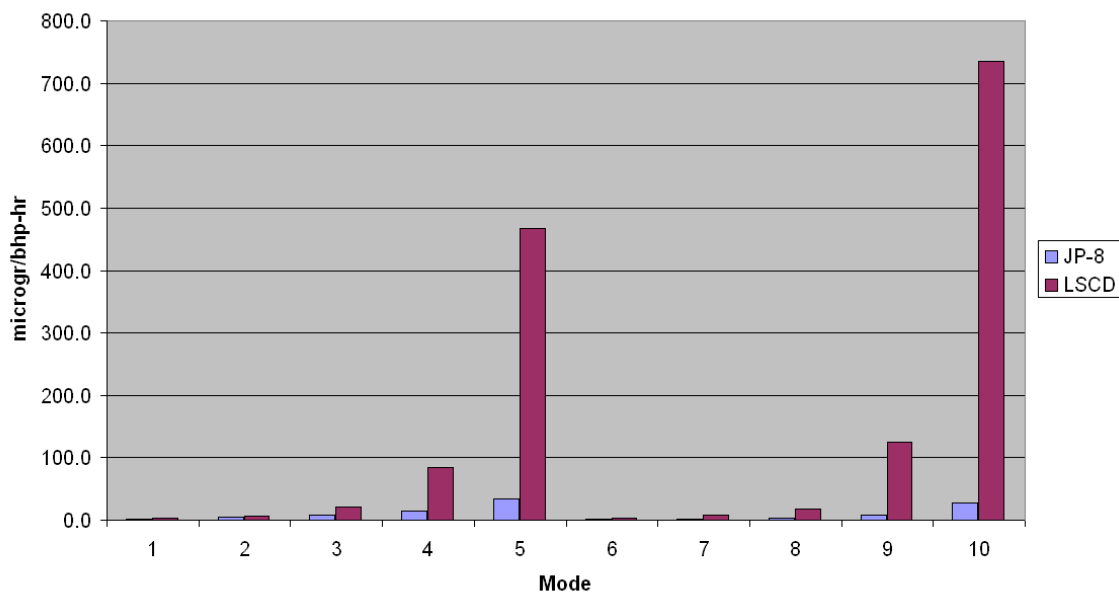
**PAH-10
Benzo(a)anthracene**



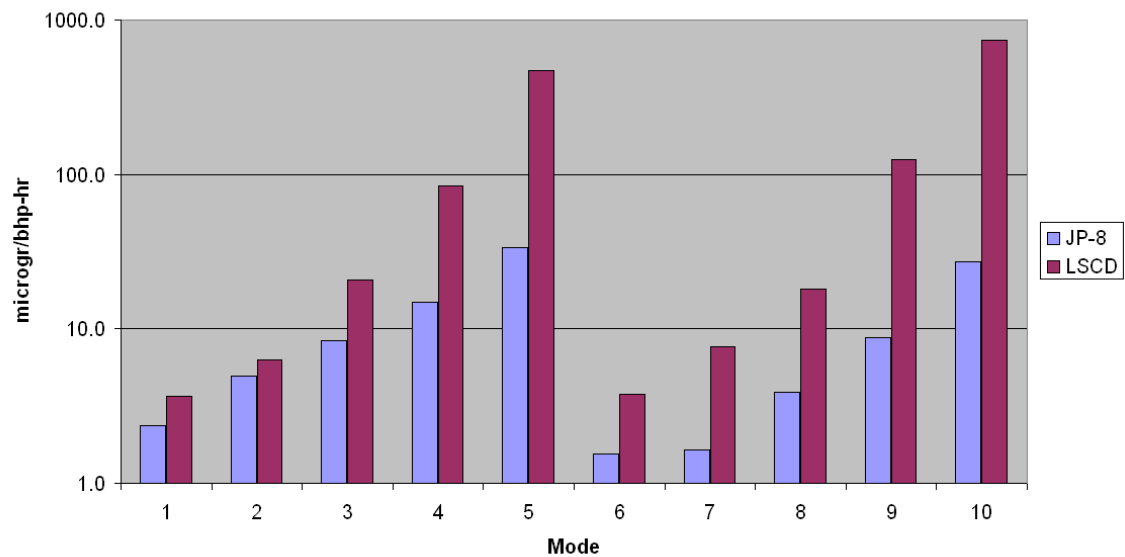
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Benzo(a)anthracene
(log scale)



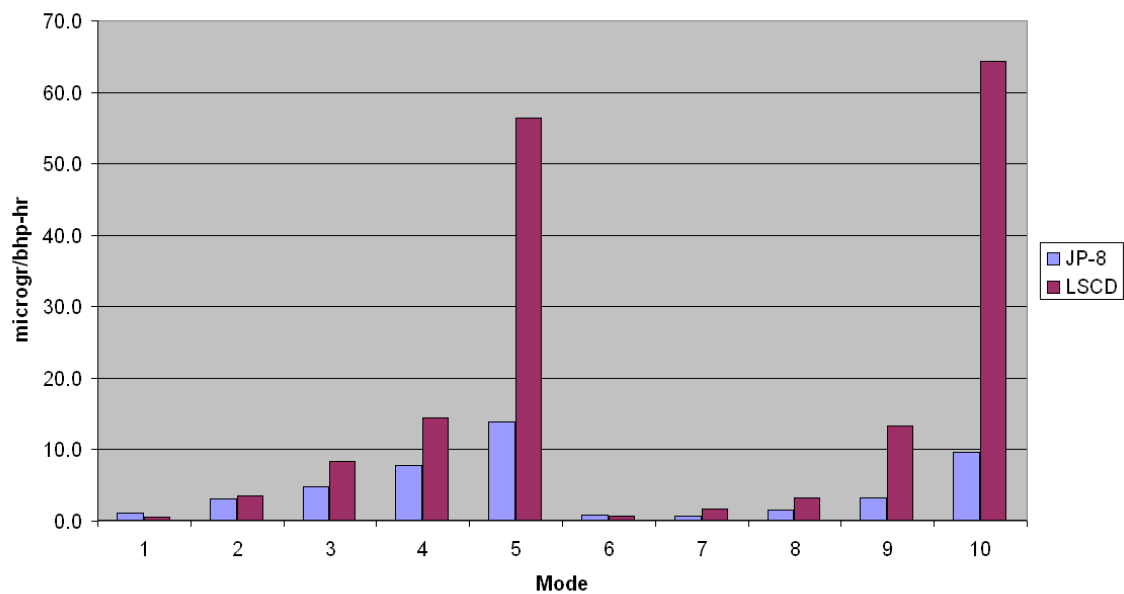
PAH-11
Chrysene



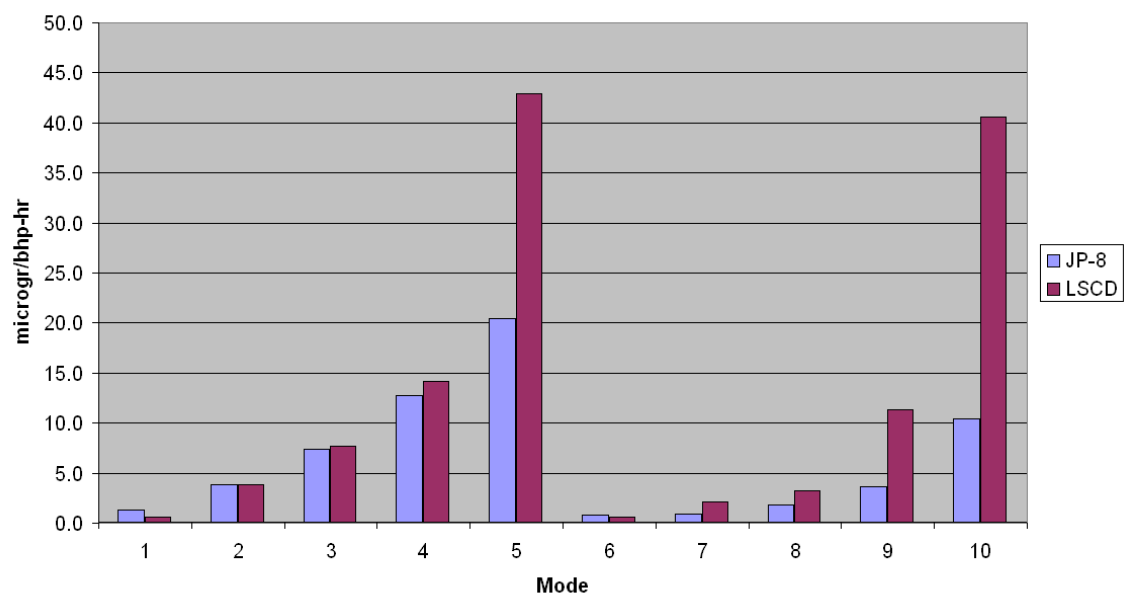
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Chrysene
(log scale)**



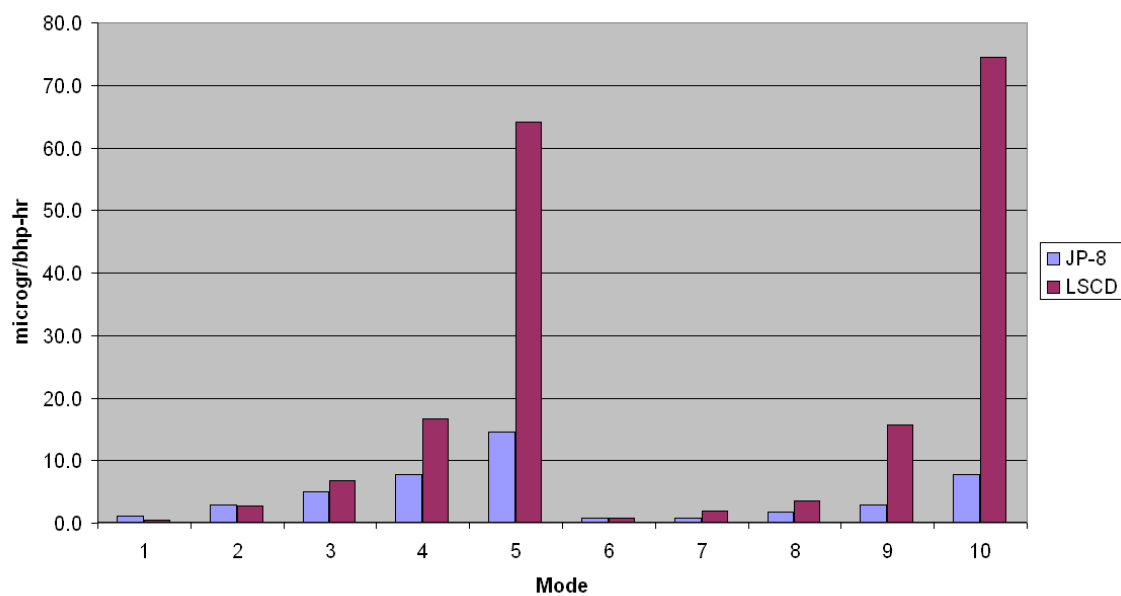
**PAH-12
Benzo(b)fluoranthene**



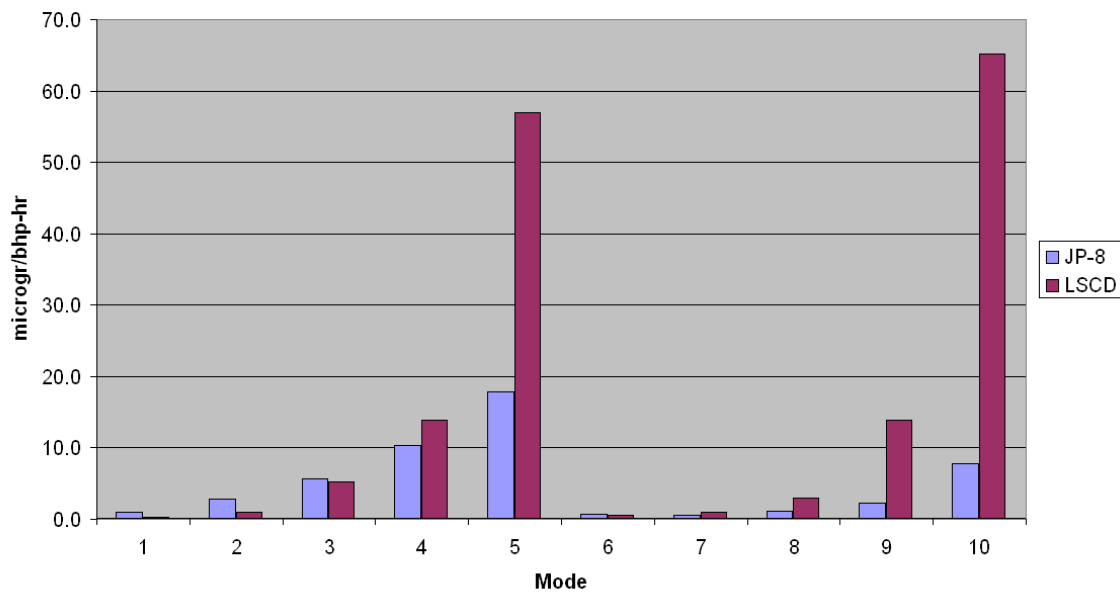
PAH-13
Benzo(k)fluoranthene



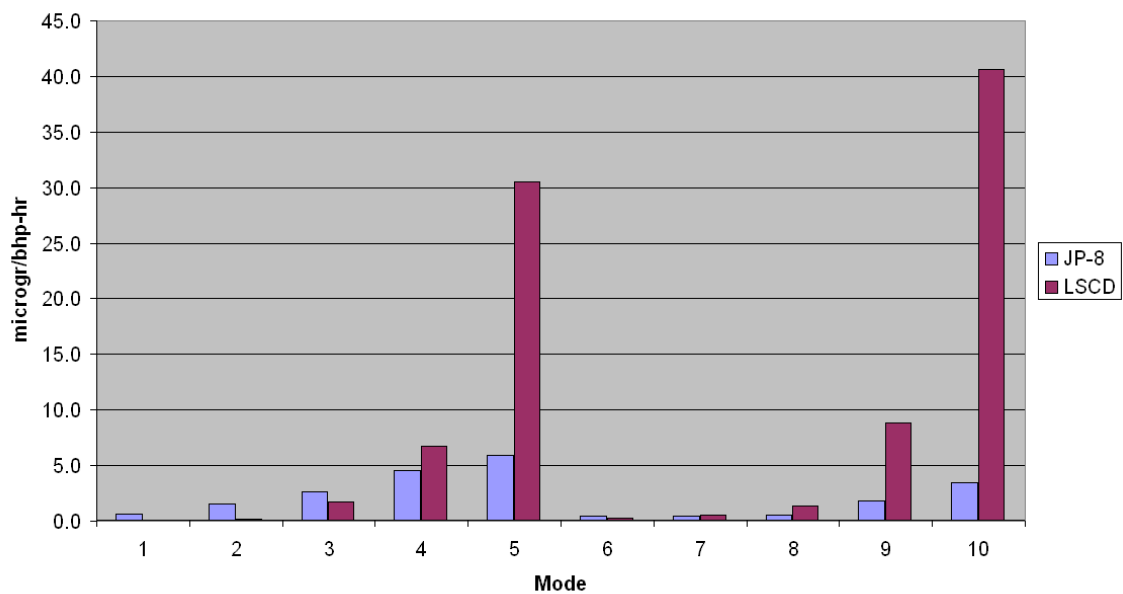
PAH-14
Benzo(e)pyrene



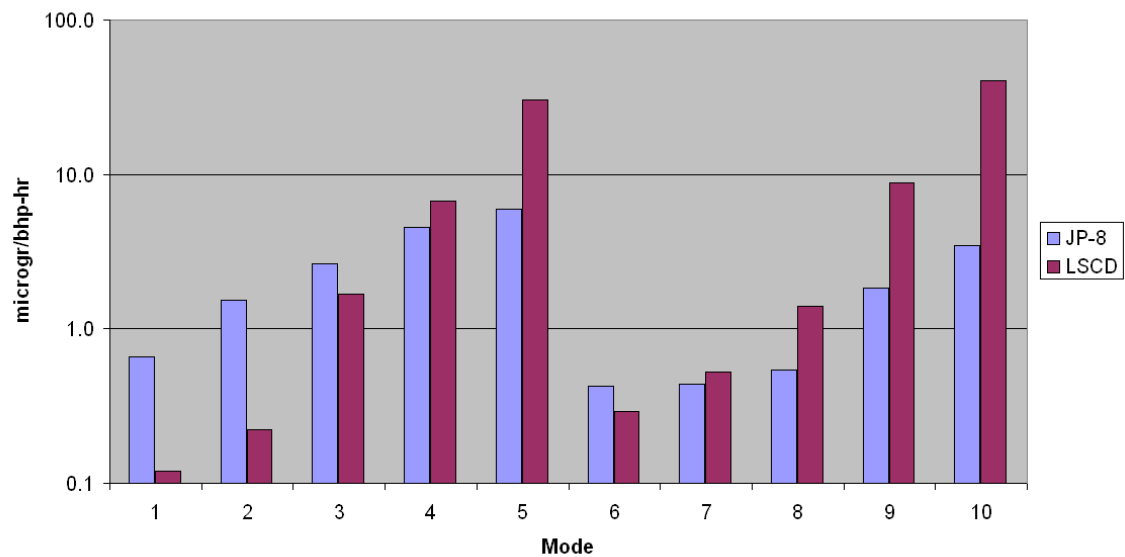
PAH-15
Benzo(a)pyrene



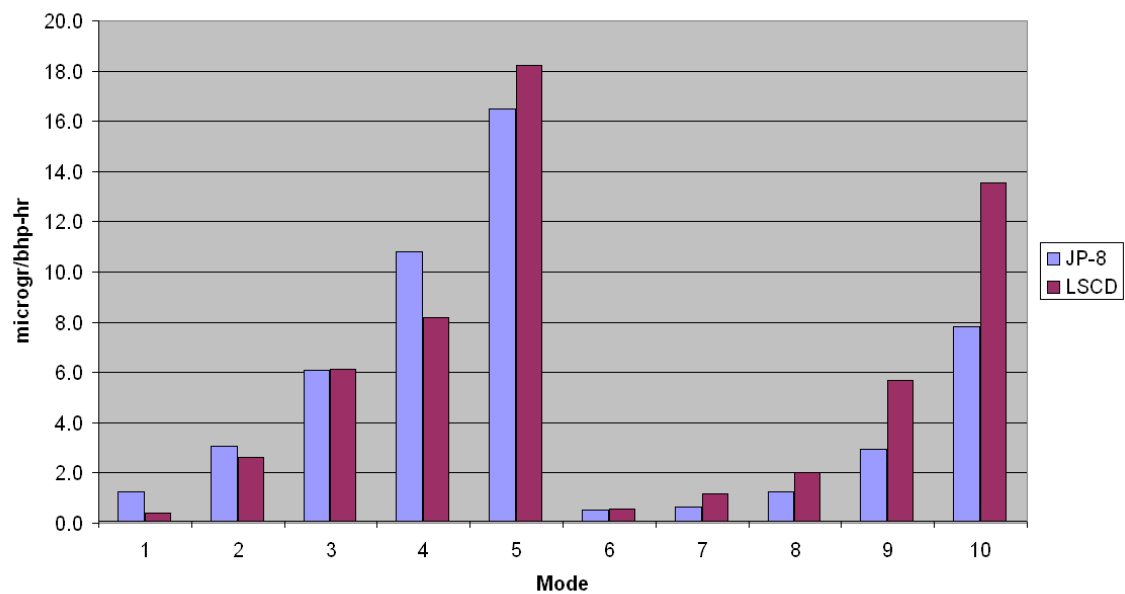
PAH-16
Perylene



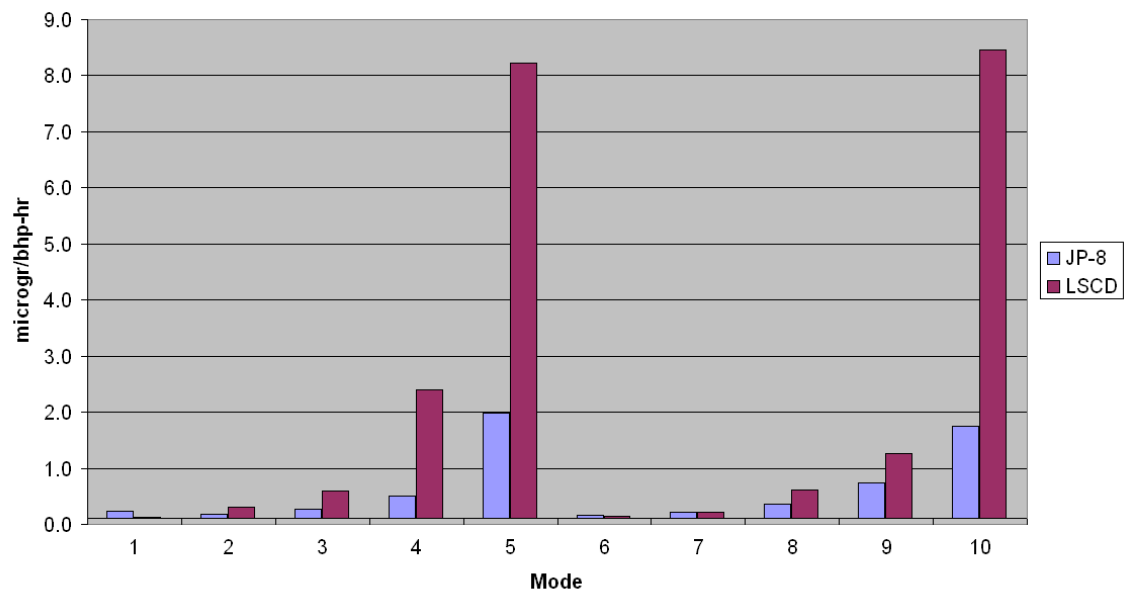
PAH-16
Perylene
(log scale)



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



PAH-18
Dibenzo(a,h)anthracene



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

