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ABSTRACT

California regulations require a maximum of 10% aromatics content in vehicular diesel fuel starting on October 1, 1993. This is in addition to the Federal regulations requiring a maximum 500 ppm sulfur content. Compliance with the low aromatics rule will require major investments in California refineries. Refiners have the potentially less-costly option of producing a higher aromatics diesel fuel if they can demonstrate equivalent emissions relative to a 10% aromatics reference fuel.

Chevron U.S.A. *Products Company has received the first* certification from the California Air Resources Board (CARB) for an alternative diesel fuel. In addition to passing the stringent CARB equivalency test for oxides of nitrogen, particulate matter, and soluble organic fraction, the certified fuel formulation performed better than the reference fuel in reducing total hydrocarbon and carbon monoxide emissions.

This paper summarizes the research and development carried out at Chevron Research and Technology Company (CRTC) leading to this fuel formulation and the CARB certification. Fuel properties for the certified fuel, as well as those for the reference fuel are also presented.

INTRODUCTION

Federal regulations require all highway diesel fuel to be limited to a maximum sulfur content of 0.05% starting October 1, 1993. Such fuels will also be limited to a minimum cetane index of 40, or a maximum aromatics content of 35%. The California Air Resources Board (CARB) has mandated an additional requirement to lower the fuel aromatics content to a maximum of 10%, effective October 1, 1993 (1).*

CARB's decision to lower the aromatics content of the fuel, as stated in their technical support document (2) was based on the best information available at the time. This included data generated in a cooperative study sponsored by the Coordinating Research Council (CRC) as part of their Vehicle Emissions Program, VE 1 (3, 4).

The CRC project used three engines to study the effects of fuel properties such as aromatics content, 90% boiling point, and sulfur level on exhaust emissions. The study concluded that all engines did not show the same effect, and that there was no simple answer to the effect of fuel properties on emissions. Although the emissions changes with respect to fuels were relatively small, the study showed that hydrocarbon (HC), carbon monoxide (CO), oxides of nitrogen (NO_x), and particulate matter (PM) emissions seemed to be reduced with fuel aromatics reduction. Lowering the fuel sulfur content helped PM reduction in all engines. Since sulfur levels were being reduced by federal regulations, CARB adopted aromatics reduction to lower diesel engine emissions further, with primary emphasis on NO_x.

CARB's emphasis on aromatics at the time might have been altered to recognize the effect of fuel cetane number, had the results of the next phase of the CRC program been available (5, 6). This phase of the program attempted to separate the effects of cetane number and aromatics content of the fuel using only one engine, the 1991 prototype DDC Series 60. The study concluded that cetane number was the key to reducing HC and CO emissions. Both cetane number and aromatics affected NO_x and PM emissions.

Lowering the aromatics content of diesel fuel from the current levels of well over 30% to those below 10% requires major capital investment and operating costs for severe hydrotreating processes in most California refineries. This is a severe financial burden during a period in which very large capital funds are needed to make the many changes required for producing reformulated gaso-

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*Numbers in parentheses designate references at the end of the paper.

ne, and for complying with a range of other environmental regulations.

CARB has allowed fuel producers the option of producing a less-costly alternative fuel with a higher aromatics content, if equivalent emissions can be demonstrated. Chevron took on the challenge of developing such an alternative fuel and spent well over $3 million in research and development to come up with a certified fuel. This effort is described in this paper.

CARB REGULATIONS

Subsection g of Section 2282, Title 13, California Code of Regulations (1), provides a detailed description of the procedure for certifying diesel fuel formulations resulting in equivalent emissions reductions. A brief summary of this procedure is given here for reference.

A candidate fuel to be tested for emissions equivalency must meet the ASTM D975 diesel fuel specifications. In addition, the following five fuel properties must also be determined:

1. Sulfur content (not to exceed 500 ppm);
2. Total aromatic hydrocarbon content;
3. Polycyclic aromatic hydrocarbon content;
4. Nitrogen content;
5. Cetane number.

Once the fuel is certified "equivalent", a producer can market the equivalent fuel as long as the first four of the above properties are not exceeded. The above determined cetane number is the minimum allowable.

The candidate fuel must be tested against a highly specified reference fuel in a Detroit Diesel Corporation (DDC) Series-60 engine, or, if CARB determines that the Series-60 is no longer representative of the post-1990 model year heavy-duty diesel engine fleet, then another engine found by CARB to be representative of such engines. One such engine is a prototype DDC Series-60 engine at Southwest Research Institute (SwRI). This engine has been calibrated to satisfy 1991 emissions standards. The reference fuel to be used in these tests has a specific set of properties which CARB determined would represent the average California 10% aromatics fuel. These properties are included in Table 1. In addition, the reference fuel must be produced from straight-run California diesel fuel by a hydrodearomatization process.

The regulations provide four choices of exhaust emissions test sequences. The first one includes both cold-start and hot-start tests. The remaining options include hot-start emissions tests only. Reference 1 contains the details.

The average emissions of NO_x, PM, and soluble organic fraction (SOF) produced by the candidate and reference fuels are compared, and must all satisfy the following to establish equivalency for fuel certification

$$C < R - \text{Delta} - Sp\,(2/n)^{1/2}\, t(a, 2n-2)$$

where:

C = Candidate fuel emissions,
R = Reference fuel emissions,
Delta = Tolerance level:
2% of R for NO_x,
4% of R for PM, and
12% of R for SOF,
Sp = Pooled standard deviation,
t = The one-sided upper percentage point of student's t distribution with a = 0.15 and 2n-2 degrees of freedom,
n = Number of tests of candidate and reference fuel.

Table 1

Reference Fuel Specifications

Property	ASTM Test Method	Specifications
Sulfur, Wt %	D 2622	500 ppm Max.
Aromatics, Vol %	D 1319*	10% Max.
Polycyclic Aromatics, Wt %	D 2425	1.4% Max.
Nitrogen, Wt %	D 4629	10 ppm Max.
Natural Cetane Number	D 613	48 Min.
Gravity, API	D 287	33-39
Viscosity at 40°C, cSt	D 445	2.0-4.1
Flash Point, °C	D 93	54 Min.
Distillation, °C	D 86	
Initial Boiling Point	171-216	(340-420 °F)
10% Recovered	204-254	(400-490 °F)
50% Recovered	243-293	(470-560 °F)
90% Recovered	288-321	(550-610 °F)
End Point	304-349	(580-660 °F)

*SFC (D 5186) now approved by CARB as an alternative

INITIAL APPROACH

Using the best information available from the CRC VE 1 study and other existing data, a fuel formulation was prepared and tested formally for CARB certification. It had a relatively low aromatics level, 22.5%, and a relatively high cetane number, 53.4, compared to average industry standards, and was designed to pass the original CARB equivalency test. The remaining properties were sulfur, 363 ppm, nitrogen, 225 ppm, and polycyclic aromatics, 6.7%. This fuel passed the PM and SOF equivalency criteria but failed the NO_x equivalency.

Shortly after this fuel was run, CARB changed the low-aromatics diesel rule to make the equivalency tests more stringent statistically. In an exploratory test, it was decided to test the effects of cetane level beyond the region explored by the CRC-VE-1 program. Accordingly, a second fuel with a very high cetane number, 62.7, was formulated. It used what we estimated to be the maximum practical amount of cetane improver considering cost, and the possibility that too high a cetane number can actually increase particulate emissions. Other properties of this fuel, with the exception of nitrogen, 862 ppm, were similar to the first fuel. This fuel failed both the NO_x and the PM equivalency criteria while passing SOF.

Based on these two exploratory failed attempts to certify a diesel fuel for the California market, it was concluded that the existing technical information at the time was not sufficient to be used as a tool to formulate an acceptable fuel. A decision was made to carry out an intensive research program, tailored to the needs of the California regulations, to study and understand the effects of fuel properties on heavy-duty diesel exhaust emissions.

TEST FACILITIES

Data for this research program were mostly generated at Chevron Research and Technology Company (CRTC) using an engine in a heavy-duty vehicle. Some research and all attempted CARB certification tests were carried out at SwRI facilities using an engine on a fixed test stand.

The engine used at SwRI was a prototype DDC Series 60 engine. This engine was the one used in the second phase of the CRC VE 1 program and represents an engine approved by CARB for fuel certification testing. The engine had a nominal rated power of 246 kW (330 hp) at 1800 rpm and was calibrated to meet 1991 emissions standards. References 5 and 6 include detailed descriptions of the engine and the test facility. Engine characteristics are reproduced from the references and are included in Table 2.

Table 2

SwRI Prototype DDC Series 60 Engine

Displacement	6-Cylinder, 11.1-Liter, 130 mm Bore x 139 Stroke
Configuration	Turbocharged, Aftercooled (Air-to-Air), Direct Injection
Emission Controls	Electronic Management of Fuel Injection Timing (DDEC-II)
Rated Power	246 kW (330 hp) at 1800 rpm With 49 kg/hr (108 lb/hr) Fuel
Peak Torque	1722 N·m (1270 Ft-lb) at 1200 rpm With 42 kg/hr (93 lb/hr) Fuel
Injection	Electronically Controlled Unit Injectors

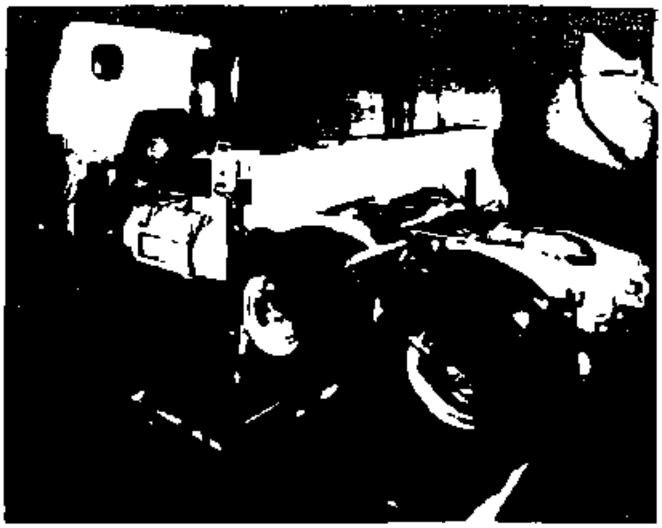

Figure 1 - Truck Chassis Dynamometer

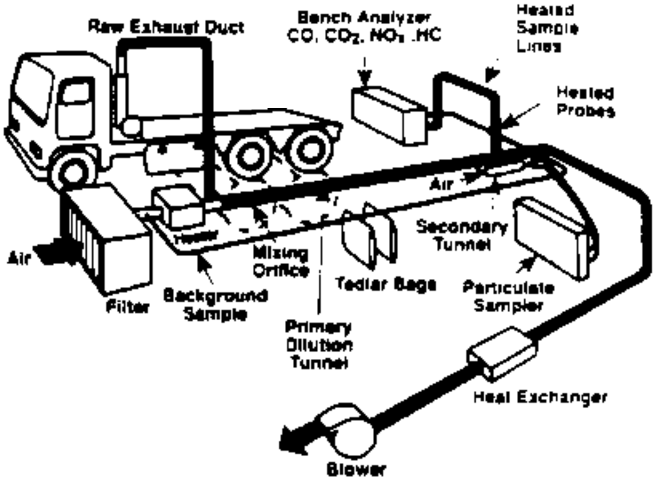

Figure 2 - Emissions Sampling System

The heavy-duty chassis dynamometer at CRTC, shown in Figure 1, is described in detail in Reference 7. This facility is capable of accommodating single and tandem axle vehicles, and can simulate a driving load up to 38,600 kg (85,000 lb) gross vehicle weight, at speeds up to 120 kph (75 mph). The chassis dynamometer was used in an engine stand emulation mode for this study. In this mode the engine output is measured directly, by installing a torque transducer on the driveshaft between the transmission and the differential, and the facility is capable of running the engine over the standard heavy-duty Federal Test Procedure (FTP) transient cycle.

Figure 2 is a diagram of the emissions sampling system. Emission measurements and sampling techniques were consistent with the FTP for transient testing of heavy-duty diesel engines (8). A Horiba exhaust emissions sampling system and Horiba analyzers were used to determine CO, NO_x, CO_2, and HC (9, 10). CO and CO_2 were detected by nondispersive infrared. NO_x detection was done using a chemiluminescent analyzer. HC analyses employed a heated flame ionization detector and heated sampling systems. Computer integration and averaging of the emissions detected during the 20-minute cycle were compared to bag samples and showed excellent agreement between the two methods. A sampler with 70 mm filters was used to collect particulate samples. These same filters were analyzed in the laboratory to determine SOF emissions for each test cycle using a Soxhlet extraction process. Carbon balance calculations, as well as gravimetric measurements using a Micromotion flowmeter, determined the fuel consumption for each cycle.

The heavy-duty engine used in the vehicle in this facility was a 1991 production DDC Series 60. This engine was specified to be as close as possible to the one used at SwRI. Engine characteristics were the same as the ones stated in Table 2 with the exception of the rated power and torque. Rated power output was 261 kW (350 hp) at 1800 rpm and peak torque was 1695 N·m (1250 ft-lb) at 1200 rpm.

FUEL PROPERTY EFFECTS ON EMISSIONS

This section covers test results related to changes in individual fuel properties such as cetane number, distillation end point, and viscosity. These properties would be in most cases, less costly to alter, or involve a lower capital expenditure, than the severe aromatics reduction. Results from a statistically designed test matrix to vary aromatics content and the cetane number simultaneously as well as those from a series of CARB certification attempts, are described in the following sections. NO_x reduction was emphasized throughout this study since it was the principal cause of the original failed attempts to certify fuels.

Properties and descriptions of all fuels discussed in this paper are summarized in Table 3. The five properties of an alternative fuel required for CARB certification are provided in each case. A brief fuel description is listed in the right-hand column for each fuel tested. Generally two

Table 3

Fuel Properties

Fuel Name	Aromatics, % D 1319*	Sulfur, ppm D 2622	Nitrogen ppm D 4629	Cetane Number, D 613	Cetane Improver %	PNA's % D 2425	Fuel Description
A	22.5	363	144	49.7	0	6.9	Base Fuel
A'	22.5	363	230	53.4-52	0.1	6.9	A With 0.1% Cetane Improver
A''	22.5	363	550	61.5	0.6	6.9	A With 0.6% Cetane Improver
B	21.7	246	102	49.4	0	5.4	B is A With EP = 600°F (85% Overhead)
B'	21.7	246	578	61.0	0.6	5.4	B With 0.6% Cetane Improver
C'	31	216	485	50.9	0.1-0.12	6.9	Reformulated Chevron Special Diesel Fuel
C''	31	216	324	59.5	0.6	6.9	C' With 0.5% Cetane Improver
D	22	738	23.8	38.6	0	3.4	Jet Fuel
D'	22	738	499	49.9	0.6	3.4	D With 0.6% Cetane Improver
E'	23.8	186	407	50.3	**	3	E' is C' With EP = 600°F (78% Overhead)
F'	25.7	186	455	51.7	0.1-0.12	**	C' With 10% Ethylene Glycol Monobutyl Ether Acetate to Add 3% O_2 to the Fuel
G'	24.9	230	527	51.6	0.1-0.12	**	Reformulated Chevron Special Diesel Fuel
J	10.8	278	102	53.2	0	**	Special Run With 3.7 cSt Viscosity
K	11.8	304	89.9	55.9	0	**	J Without 7% of the Light Ends to Increase Viscosity to 4.13 cSt
P	1.1	<0.6	0.21	62.5	0	~0	Special Run Low Aromatics Diesel Fuel
A2	18.8	54	441	58	0.185	2.22	19/58 Aromatics/Cetane
B2	12.8	37	281	50.5	0	2.11	13/50 Aromatics/Cetane
C2	12.7	35	311	57.6	0.023	1.65	13/58 Aromatics/Cetane
D2	15.7	44	308	54.7	0.015	2.56	16/54 Aromatics/Cetane
E2	18.5	54	301	50.1	0	2.62	19/50 Aromatics/Cetane
F2	18.8	196	466	58.9	0.185	4.39	19/59/200 Aromatics/Cetane/Sulfur
G2	15.1	202	341	54.8	0	3.51	15/55/200 Aromatics/Cetane/Sulfur
R2	9.6	412	31	49.2	0	3.35	Reference Fuel

*SFC D 5186 used for A2 through G2
**Not measured

Table 4

SwRI - Phase A

		A'			P			Comparison
		Mean	SDEV	CV %	Mean	SDEV	CV %	
NO_x	g/bhp-Hr	4.1780	0.061	1.47	3.9180	0.055	1.41	P is 6.22% Lower Than A'
PM		0.1700	0.005	2.85	0.1360	0.003	1.90	P is 20% Lower Than A'
SOF		0.0502	0.012	23.90	0.0481	0.011	23.60	P is 4.2% Lower Than A'
CO		1.2880	0.033	2.56	1.1120	0.037	3.32	P is 13.7% Lower Than A'
HC		0.1480	0.008	5.40	0.1230	0.008	6.33	P is 16.9% Lower Than A'
BSFC	Lb/bhp-Hr	0.3970	0.004	0.97	0.3900	0.005	1.39	P is 1.28% Higher Than A'
Work	bhp-Hr	22.193	0.04	0.19	21.97	0.105	0.48	P is 1.66% Lower Than A

tables are associated with each phase of this study. One includes detailed emissions data for each test in the sequence it was run. These tables are attached as Appendix I. The other provides a summary of test results for each phase and includes the mean and the standard deviation for the data presented in the first table.

INITIAL SwRI TESTS - One set of engine tests was carried out at SwRI prior to initiating the CRTC experiments. This set, Phase A, included Fuel A' and Fuel P. A' was the fuel used in the first exploratory certification attempt. It contained around 22% aromatics and had a cetane number of around 53, using 0.1 wt % cetane improver additive. P was an experimental fuel produced in a distillate hydrotreater with almost no aromatics, sulfur, or nitrogen. It had a very high natural cetane number of around 62. The goal was to determine the maximum benefit one could achieve if aromatics were lowered to an extremely low level, well beyond the regulated 10%, while the cetane number was high. This phase would also provide data to relate Fuel P to A', and therefore, indirectly to the reference fuel, since very little of A' and reference fuel existed. Sufficient supply of Fuel P was on hand. Comparison between the two engines could also be made if the same fuels were tested at CRTC.

The test sequence and individual fuel test data are presented in Table I-1 of Appendix I. Each test consisted of two back-to-back hot-start transient emissions cycles. On the first day, Fuel A' was tested once and Fuel P was tested twice. On the second day the order was reversed. Table 4 includes the results. This testing demonstrated that:

1. Emissions from Fuel P were significantly lower than those of A' in all cases;
2. The maximum range for NO_x reduction based on the lowest aromatics and a very high cetane level was around 6%;
3. *Day-to-day data variation was significant.* Therefore, conclusions should not be made based on data from a single day.

INITIAL CRTC TESTS - The first series of tests at CRTC used the same fuels used at SwRI (i.e., A' and P) to compliment the results obtained in Phase A and to compare the two engines. Two additional fuels were included in this series, Phase B, and were designated A and A". A was the base fuel from which A' had been prepared. It contained no cetane improver and had a natural cetane number around 50. A" was the same base fuel with a high level of cetane improver, 0.6%, to match the cetane number of Fuel P at around 62. The use of cetane improver additive affects the nitrogen content of the fuel. Other properties are unchanged. Phase B at CRTC had similar goals to the ones stated above for Phase A at SwRI.

Fuels were tested using a "Latin Square" sequence. The order was selected randomly and is shown in Table 5. Each fuel was tested four times on the scheduled day

Table 5

Test Sequence for CRTC Phase B

	Week 1	Week 2	Week 3	Week 4
Day 1	A	A"	A'	P
Day 2	A"	A	P	A'
Day 3	A'	P	A	A"
Day 4	P	A'	A"	A

The entire test lasted 4 weeks. Detailed emissions data for all four fuels are included in Tables I-2 through I-5 in Appendix I. Table 6 is a summary of the results for Phase B. These results confirm that the two engines yield different results but the trends are similar. The NO_x difference between A' and P was around 10% on the CRTC engine. The engine at CRTC has higher NO_x emissions and lower PM and HC emissions when compared to the one at SwRI. Enough day-to-day variation and drift existed that future tests should include testing of more than one fuel per day.

END POINT EFFECT - The effect of lowering the end point of the boiling range was investigated in Phase C. *Fuel A' was processed to remove 15% of the heavy end.* This reduced the end point from 330°C (625°F) to 316°C (600°F). The cetane improver was also raised from 0.1% to 0.6%. The resulting fuel, B", which had a 61 cetane number, was tested along with A' in a 4-day test sequence which consisted of running both fuels on each day. Data are included in Table I-6 in Appendix I. Results are summarized in Table 7. NO_x emissions for B" were about 2% lower than A'. NO_x emissions for A" were 1.3% lower than A' in the previous phase. Comparison of the results from these two phases shows that the NO_x reduction for B" was mostly due to the use of the cetane improver and not the end point adjustment.

In order to confirm this conclusion, additional tests were conducted in Phase D using end point adjustment only. Two fuels were tested in the same pattern as above. One fuel, C', was the low sulfur, cetane-improved fuel Chevron markets in the Los Angeles area as reformulated Chevron Special Diesel Fuel. This fuel was redistilled to remove 22% of the heavy end, reducing the end point from 345°C (653°F) to 316°C (600°F). It was designated as Fuel E'. No other changes were made. No additional cetane improver was used.

Table I-7 in Appendix I includes the data generated in this phase. Table 8 contains the summary of the results. Once again it was confirmed that lowering of the end point did not improve the exhaust emissions, and that the improvements in the previous phase were mostly due to the use of cetane improver additive.

BEST CURRENT COMMERCIAL LOW SULFUR FUEL - Phase E, presented in Table I-8 in Appendix I and summarized in Table 9, was an attempt to evaluate whether the reformulated Chevron Special Diesel Fuel, C', with the addition of a high level of cetane improver had the potential to be certified as an alternative fuel. Thus, C" was created by adding 0.5% cetane improver additive to Fuel C'. The test sequence was the same as above using both *fuels every day for 4 days.*

The earlier tests, which related emissions from existing fuels and CRTC engine performance to emissions from the initial certification attempts and other tests at SwRI, were used as a tool to judge if a fuel had a chance to be certified. Although NO_x emissions for the additized fuel were improved by 1.4% compared to the commercial fuel, the reduction was not sufficient to consider fuel certification.

JET FUEL - It is common practice to blend jet fuel with No. 2 diesel fuel in winter months to reduce the cloud point of the fuel to comply with ASTM D 975. Our understanding of the CARB low aromatics diesel regulation is that winter blending can only be done if each component is a certified fuel. Therefore, typical commercial jet fuel, D, and the same fuel with 0.6% cetane improver additive were tested in Phase F. Table I-9 in Appendix I and Table 10 contain the emissions data and the results.

Although NO_x, PM, and SOF were all lowered by the use of the cetane improver additive, the reductions were not sufficient to make the cetane-improved jet fuel a possible candidate for certification. In this case the fuel had a relatively low aromatics content but the cetane number could not be raised high enough to lower the emissions far enough to match reference fuel performance.

OXYGENATES - Phase G included a limited study of the use of an oxygenate component in the fuel. Table 11 includes a list of several oxygenated solvents and their properties. We set the following requirements for selecting the one we tested:

1. The oxygenate should be miscible with the diesel fuel.
2. Its flash point should not be lower than 140°F.
3. Water solubility should be low to avoid haze problems.
4. *It should have a high oxygen content to* be feasible.

It should be noted that the typical amounts of any oxygenate used in diesel fuel (several volume percent) make it a fuel blend component and not a fuel additive. The above four requirements limited the choice of components to two: ethylene glycol monobutyl ether acetate and 2-ethylhexyl acetate. The former was selected for testing

Table 6

CRTC - Phase B

		A			A'			A''			B		
		Mean	SDEV	CV %	Mean	SDEV	CV %	Mean	SDEV	CV %	Mean	SDEV	[illegible]
NO_x	g/bhp-Hr	5.49	0.077	1.40	5.48	0.168	3.07	5.41	0.129	2.39	4.95	[illegible]	[illegible]
PM		0.093	0.006	6.57	0.094	0.007	7.84	0.087	0.01	11.53	0.077	[illegible]	[illegible]
SOF		0.04	0.007	16.58	0.03	0.004	13.31	0.03	0.005	16.96	0.03	0.003	[illegible]
CO		1.67	0.053	3.19	1.70	0.15	3.81	1.66	0.096	5.79	1.54	[illegible]	[illegible]
HC		0.06	0.017	27.65	0.04	0.008	19.26	0.04	0.013	31.74	0.03	[illegible]	[illegible]
BSFC	(Carbon) Lb/bhp-Hr	0.39	0.007	1.80	0.39	0.007	1.87	0.39	0.006	1.59	0.38	[illegible]	[illegible]
BSFC	(Gravimetric) Lb/bhp-Hr	0.41	0.016	3.89	0.41	0.025	6.10	0.40	0.017	4.21	0.41	[illegible]	[illegible]
Work	bhp-Hr	21.75	0.094	0.43	21.76	0.135	0.62	21.75	0.096	0.44	21.43	[illegible]	[illegible]

Table 7

CRTC - Phase C

		[illegible]			B'		
		Mean	SDEV	CV %	Mean	SDEV	CV %
NO_x	g/bhp-Hr	5.55	0.0932	1.68	5.43	0.094	1.73
PM		0.095	0.0068	7.18	0.093	0.0087	9.39
SOF		0.03	0.0021	7.06	0.03	0.0021	5.99
CO		1.79	0.143	7.99	1.69	0.170	10.06
HC		0.03	0.0069	23.01	0.04	0.005	12.34
BSFC	(Carbon) Lb/bhp-Hr	0.39	0.0069	1.76	0.39	0.0070	1.80
BSFC	(Gravimetric) Lb/bhp-Hr	0.40	0.014	3.53	0.40	0.013	3.23
Work	bhp-Hr	21.55	0.082	0.38	21.59	0.108	0.50

Table 9

CRTC - Phase E

		[illegible]			[illegible]		
		Mean	SDEV	CV %	Mean	SDEV	[illegible]
NO_x	g/bhp-Hr	5.85	0.0772	1.32	[illegible]	[illegible]	[illegible]
PM		0.104	0.0039	[illegible]	[illegible]	[illegible]	[illegible]
SOF		0.03	0.0036	[illegible]	[illegible]	[illegible]	[illegible]
CO		2.06	0.069	[illegible]	[illegible]	[illegible]	[illegible]
HC		0.02	0.0074	[illegible]	[illegible]	[illegible]	[illegible]
BSFC	(Carbon) Lb/bhp-Hr	0.40	0.0075	[illegible]	[illegible]	[illegible]	[illegible]
BSFC	(Gravimetric) Lb/bhp-Hr	0.41	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Work	bhp-Hr	21.55	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 8

CRTC - Phase D

		C'			E		
		Mean	SDEV	CV %	Mean	SDEV	CV %
NO_x	g/bhp-Hr	5.70	0.0747	1.31	5.70	0.040	[illegible]
PM		0.102	0.007	6.97	0.099	0.011	11.23
SOF		0.03	0.0012	3.98	0.03	0.0039	12.98
CO		1.98	0.168	9.46	2.00	0.075	3.77
HC		0.04	0.0129	32.17	0.04	0.016	41.24
BSFC	(Carbon) Lb/bhp-Hr	0.40	0.0076	1.89	0.40	0.0064	1.60
BSFC	(Gravimetric) Lb/bhp-Hr	0.41	0.005	1.27	0.40	0.005	1.32
Work	bhp-Hr	21.66	0.063	0.29	21.55	0.071	0.33

Table 10

CRTC - Phase F

		[illegible]			[illegible]		
		Mean	SDEV	CV %	Mean	SDEV	[illegible]
NO_x	g/bhp-Hr	5.82	0.1490	2.56	[illegible]	[illegible]	[illegible]
PM		0.101	0.0043	4.28	0.092	[illegible]	[illegible]
SOF		0.04	0.0012	2.90	[illegible]	[illegible]	[illegible]
CO		1.93	0.089	4.63	[illegible]	[illegible]	[illegible]
HC		0.07	0.0132	19.86	[illegible]	[illegible]	[illegible]
BSFC	(Carbon) Lb/bhp-Hr	0.40	0.0083	[illegible]	[illegible]	[illegible]	[illegible]
BSFC	(Gravimetric) Lb/bhp-Hr	0.41	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Work	bhp-Hr	21.25	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 11

Oxygenates as Potential Diesel Fuel Additives

Oxygenate	Flash Point, F	Solubility % Water in Solvent	Oxygen Mass %	Mass % Oxygenate to 1% O	Vol % Oxygenate in DF	Lb/Gal	Cost* (Est.) $/Lb	Cost (Est.) $/Gal	Extra Cost (1%) $/Gal
Secondary Butyl Alcohol	32	30	22	5	5.3	6.72	0.67	4.50	0.24
Isopropyl Acetate	35	1.8	31	3.2	3.1	7.26	0.53	3.85	0.12
Ethylene Glycol Monobutyl Ether	143	100	27	3.7	3.5	7.49	0.42	3.15	0.11
Propylene Glycol Methyl Ether	89	100	36	2.8	2.6	7.65	0.59	4.51	0.12
Propylene Glycol Butyl Ether	113	14.5	24	4.2	4.1	7.30	0.60 (1)	4.38	0.18
Diisopropyl Ether	62	100	27	3.7	4.3	6.08	0.46	2.80	0.12
Dimethyl Carbonate	62	**	53	1.9	1.5	8.9	1.40	12.46	0.19
Ethylene Glycol Monobutyl Ether Acetate	165	1.6	30	3.3	3.0	7.84	0.83	6.51	0.19
Dibasic Esters	212	3.1	40	2.5	2.0	9.09	**		
Diisobutyl Ketone	140	0.8	11	9.1	9.5	6.76	0.62	4.19	0.40
2-Ethylhexanol	166	2.6	12	8.3	8.5	6.94	0.50	3.47	0.29
2-Ethylhexyl Acetate	160	0.55	19	5.3	5.2	7.27	0.73	5.31	0.28
Ethyl Glyme	81	3.3	27	3.7	3.8	7.00	1.65	11.55	0.44
Butyl Diglyme	244	1.4	22	5	4.8	7.36	2.70 (2)	19.87	0.95

*Costs were obtained from Chemical Marketing Reporter
**Not Available

due to its higher flash point and higher oxygen content. Fuel F' was prepared by adding 10 wt % ethylene glycol monobutyl ether acetate to Fuel C', Reformulated Chevron Special Diesel Fuel. The oxygen content of the resulting blend was 3% by weight.

Table I-10 in Appendix I includes the emissions data from Phase G. This information is summarized in Table 12. PM and CO were each reduced by about 18% but NO_x emissions increased by over 3%. No further testing was conducted using oxygenates due to the adverse effect on NO_x.

DDC ENGINE CONTROL - The 1991 DDC engine used at CRTC should have been a 5-g NO_x engine. Although most fuels tested on this engine were experimental, it was felt that NO_x emissions were higher than expected. A new engine electronic control module was obtained from DDC and installed. Phase H, as presented in Table I-11 in Appendix I and Table 13, includes a series of tests with one fuel, G1; another batch of reformulated Chevron Special Diesel Fuel. Tests were conducted before and after the new control was installed. On the average NO_x emissions were reduced by 7.6%, from 5.54 to 5.12 g/bhp-hr. The previous conclusions are not affected by this change since relative differences were observed. However, comparison of absolute data from this point on to the data prior to this change would have to take this difference into account.

VISCOSITY - The last fuel property considered was viscosity. A noncommercial 10% aromatics diesel fuel, J, with a viscosity of 3.7 cSt at 40°C, was used as one fuel. Fuel J was processed to remove 7% of the light ends of the boiling range and designated Fuel K. Fuel K's viscosity was 4.13 cSt. The goal was to make minimum changes to other properties such as aromatics content and the cetane number in order to test the effect of viscosity alone.

Results from this part of the study, Phase I, are presented in Table I-12 in Appendix I and Table 14. The differences were generally not large enough to be considered for fuel certification. NO_x emissions were raised by 0.6% with the higher viscosity fuel. PM was increased by about 4% and SOF remained constant.

Table 12

CRTC - Phase G

		[illegible]			[illegible]		
		Mean	SDEV	CV %	Mean	SDEV	CV %
NOx	g/bhp-Hr	5.59	0.1859	[illegible]	5.32	[illegible]	[illegible]
PM		[illegible]	[illegible]	[illegible]	[illegible]	0.105	[illegible]
SOF		[illegible]	[illegible]	[illegible]	[illegible]	0.050	[illegible]
CO		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
HC		[illegible]	[illegible]	19.34	[illegible]	[illegible]	[illegible]
BSFC	(Carbon) Lb/bhp-Hr	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
BSFC	(Gravimetric) Lb/bhp-Hr	0.42	0.005	[illegible]	[illegible]	0.006	[illegible]
Work	bhp-Hr	[illegible]	[illegible]	[illegible]	21.34	0.049	[illegible]

Table 13

CRTC - Phase H

		D1 Before			D1 After		
		Mean	SDEV	CV %	Mean	SDEV	CV %
NOx	g/bhp-Hr	5.54	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
PM		[illegible]	0.0047	4.45	[illegible]	0.0057	[illegible]
SOF		0.03	0.0008	2.78	0.03	[illegible]	4.72
CO		[illegible]	0.0998	5.33	[illegible]	[illegible]	5.63
HC		0.03	0.008	26.57	0.03	0.0039	12.89
BSFC	(Carbon) Lb/bhp-Hr	0.40	0.0063	1.58	0.41	[illegible]	1.25
BSFC	(Gravimetric) Lb/bhp-Hr	0.40	0	0.00	0.42	0.0052	1.24
Work	bhp-Hr	21.39	[illegible]	[illegible]	21.34	[illegible]	[illegible]

AROMATICS AND CETANE NUMBER EFFECTS ON EMISSIONS

Results presented in the previous section reveal that there is no inexpensive and simple method to certify a diesel fuel to CARB's requirements. No existing commercial fuel could be modified by simple methods, such as cetane improver additive addition, to satisfy the test requirements.

A major effort was initiated to study the effects of varying the fuel's aromatics content and cetane number simultaneously within a practical range. Our previous experience suggested aromatics would have to be at or below the 20% level. On the other hand, there was no need to test levels close to 10%, since fuel produced at this level required no certification. We, therefore, selected the fuel aromatics range to be from 13% to 19%. Similar reasoning resulted in selecting a cetane number range of 50 to 58.

Table 14

CRTC - Phase I

		[illegible]			[illegible]		
		Mean	SDEV	CV %	Mean	SDEV	CV %
NOx	g/bhp-Hr	4.10	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
PM		0.094	0.006	5.364	0.098	[illegible]	[illegible]
SOF		0.025	0.004	[illegible]	0.025	[illegible]	[illegible]
CO		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
HC		0.03	[illegible]	42.75	[illegible]	[illegible]	[illegible]
BSFC	(Carbon) Lb/bhp-Hr	0.38	0.004	[illegible]	[illegible]	[illegible]	[illegible]
BSFC	(Gravimetric) Lb/bhp-Hr	0.40	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Work	bhp-Hr	21.25	0.028	[illegible]	[illegible]	[illegible]	[illegible]

Table 15

CRTC - Phase J

		B2 (13/50)			C2 (13/58)			D2 (16/54)			E2 (19/50)			A2 (13/58)		
		Mean	SDEV	CV %	Mean	SDEV	CV %	Mean	SDEV	CV %	Mean	SDEV	CV %	Mean	SDEV	CV %
NOx	g/bhp-Hr	4.86	0.107	2.20	4.72	0.114	2.41	4.86	0.098	2.01	5.00	0.086	1.72	4.9	0.093	[illegible]
PM		0.089	0.004	4.197	0.087	0.004	4.901	0.090	0.005	5.040	0.09	0.009	9.77	0.09	0.004	[illegible]
SOF		0.024	0.001	3.973	0.023	0.002	10.099	0.024	0.002	7.055	0.024	0.004	17.208	0.03	0.008	[illegible]
CO		1.71	0.046	2.71	1.68	0.101	6.03	1.73	0.094	5.45	1.75	0.103	5.87	[illegible]	[illegible]	4.67
HC		0.035	0.007	19.260	0.032	0.010	32.470	0.028	0.010	36.350	0.033	0.008	23.350	0.027	[illegible]	[illegible]
BSFC	(Carbon) Lb/bhp-Hr	0.39	0.01	2.63	0.39	0.012	2.98	0.39	0.008	2.13	0.39	0.011	2.75	0.4	[illegible]	[illegible]
BSFC	(Gravimetric) Lb/bhp-Hr	0.40	0.013	3.37	0.40	0.015	3.68	0.39	0.016	4.17	0.40	0.013	3.29	0.4	[illegible]	[illegible]
Work	bhp-Hr	21.28	0.036	0.17	21.29	0.04	0.19	21.29	0.032	0.15	21.29	0.047	0.22	[illegible]	[illegible]	[illegible]

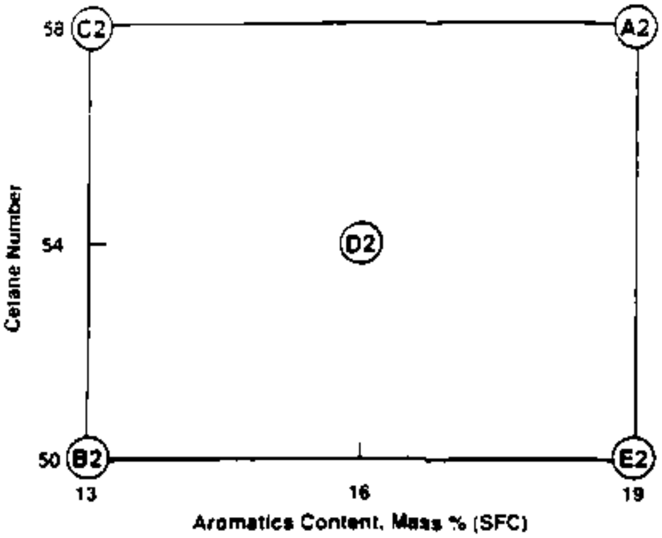

Figure 3 - Five Fuel Test Matrix

A five-fuel test matrix was designed statistically to map out the above ranges of aromatics and cetane number. Figure 3 relates the fuel names, A2, B2, C2, D2, and E2 to these two properties. Additional properties for these five fuels are given in Table 3. Fuels were tested in a 20-day period which made it possible to test three fuels per day in a balanced, incomplete block design. One hot-start transient emissions test was conducted per day for each of three fuels. The test sequence was designed so that the last fuel tested on each day was the first fuel tested on the next day. Each fuel was tested the same number of times over the 20-day test period. The complete data set for this series of tests, Phase J, is included in Table II-1 in Appendix II. Table 15 contains the summary of the data.

A statistical analysis was applied to determine if fuel effects in each case were significant at the 95% confi-ence level. The results are summarized in Table 16. etane number and aromatics have a significant effect on O_x. The Tukey Multiple Comparison Procedure was ilized to determine that, with respect to NO_x emissions, uel C2 was clearly the lowest. Fuels D2, B2, and A2, ere about the same and higher, while E2 was the ghest.

Table 16

The Significance of Fuel Properties on Emissions

	Cetane	Aromatics
NO_x	Yes	Yes
Particulate	No	Yes
SOF	No	No

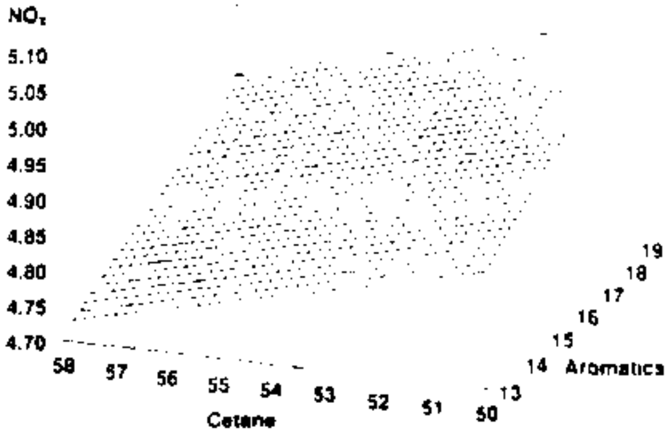

Figure 4 - Distribution of NO_x as a Function of Cetane and Aromatics

A predictive model for NO_x as a function of cetane number and aromatics was developed from this data set and is given as follows:

$$NO_x = 5.296 - (0.0161)\,(\text{Cetane}) + (0.0281)\,(\text{Aromatics})$$

An interactive term between cetane and aromatics was found to be insignificant and was, consequently, dropped from the model. Figure 4 is a graphic view of the mapped region of aromatics and cetane number and their effect on NO_x emissions.

REFERENCE FUEL RELATIONSHIP

The final phase of this study at CRTC, Phase K, included testing a reference fuel. By this time a limited quantity of reference fuel had been produced in pilot plant facilities at CRTC. Reference fuel production was a very time consuming and expensive process. We estimated the production cost to be well over $300 per gallon. It was, therefore, necessary to minimize the amount of fuel used in this phase of our study in order to conserve this fuel for certification tests at SwRI.

A 4-day test sequence was chosen to test the reference fuel with the best (C2) and the worst (E2) of the five fuels used in the previous test matrix. One hot-start emissions test was conducted on each of the three fuels per day. This allowed direct comparison of all fuels to the reference fuel. Table II-2 in Appendix II includes the complete data set. Table 17 contains the summary. Tukey's Multiple Comparison Procedure was used to determine which fuels were significantly different at the 95% confidence level. The results are summarized in Table 18. Based on these results we were optimistic that even the worst of the five fuels, E2, with the highest level of aromatics and the lowest cetane number would have a good chance to be certified. This fuel, if certified, would potentially be the least costly of all five to produce

Table 17

CRTC - *Phase K (Reference)*

		C2 (13.58)			E2 (19.50)			R2 Reference		
		Mean	SDEV	CV %	Mean	SDEV	CV %	Mean	SDEV	CV %
NO_x	g/bhp-Hr	4.74	0.096	2.03	4.88	0.063	1.30	4.99	0.108	2.16
PM		0.088	0.002	2.075	0.096	0.005	5.446	0.1	0.005	4.77
SOF		0.023	0.002	7.938	0.025	0.003	10.328	0.03	0.001	5.763
CO		1.75	0.094	5.36	1.86	0.135	7.24	1.98	0.103	5.21
HC		0.02	0.005	22.22	0.03	0.005	15.38	0.03	0.005	18.18
BSFC	(Carbon) Lb/bhp-Hr	0.38	0.006	1.50	0.38	0.005	1.31	0.38	0.01	2.60
BSFC	(Gravimetric) Lb/bhp-Hr	0.39	0.015	3.82	0.40	0.008	2.04	0.4	0.019	4.76
Work	bhp-Hr	21.30	0.047	0.22	21.48	0.294	1.37	21.3	0.023	0.11

FUEL CERTIFICATION ATTEMPTS

We attempted to certify five fuels at SwRI following the conclusion of the research effort at CRTC. These fuels are listed in Table 19 with additional properties provided in Table 3. The first three fuels were selected from the five-fuel test matrix discussed above. The final fuels, F2 and G2, were new formulations developed based on the results from the first three. CARB regulations and procedures described in an earlier section of this paper were followed throughout each qualification test. The hot-start emissions test option was selected. This option requires a minimum of 10 days of testing but has the most attractive statistical equivalency test. The test order on each day consisted of testing the reference fuel once, the candidate fuel twice, and the reference fuel once again.

Tables III-1 through III-5 in Appendix III contain the complete set of results for each fuel tested. Mean and standard deviation values for each case are shown on the bottom of each table. Testing for Fuel E2 was halted after 4 days when it became obvious that it had no chance to pass. This would have been the most economic of all fuels to produce since it had the highest aromatics level and the lowest cetane number.

Table 18

The Significance of Fuel Differences in Emissions

	R2 Vs. E2	R2 Vs. C2	E2 Vs. C2
NO_x	No	Yes	Yes
Particulate	Yes	Yes	Yes
SOF	No	Yes	Yes

Table 19

Fuels Used in the Certification Process

Fuel Name	Aromatics, Wt % (SFC)	Cetane Number	Sulfur, Wt ppm	Test Result
E2	18.5	50	54	Failed
A2	19	58	54	Passed
D2	16	55	44	Failed
F2	19	59	196	Passed
G2	15	55	202	Passed

Fuel A2 with the same level of aromatics but much higher cetane number passed and became the first fuel to be certified by CARB. Although NO_x emissions were 0.92% higher than that of the reference fuel, the equivalency criterion in the regulation, which includes a 2% tolerance level for NO_x, allowed the fuel to pass. Reference to Table III-2 will also show that HC emissions for this fuel *were 37.5% better than the reference fuel.* CO was 24% better, particulate was 2.5% lower, and SOF was 10% lower. In fact in all cases, including the failed attempts, the HC and CO benefit is impressive, despite the fact they are not credited in the regulations.

Fuel D2 with a lower aromatics level along with lower cetane number was tested next. This fuel failed narrowly.

The above three fuels, including A2 which passed, had very low sulfur levels to ensure a sufficiently low emissions level for particulate matter. Examination of the results indicated that there was a good chance to increase the sulfur level to a more practical level in future tests.

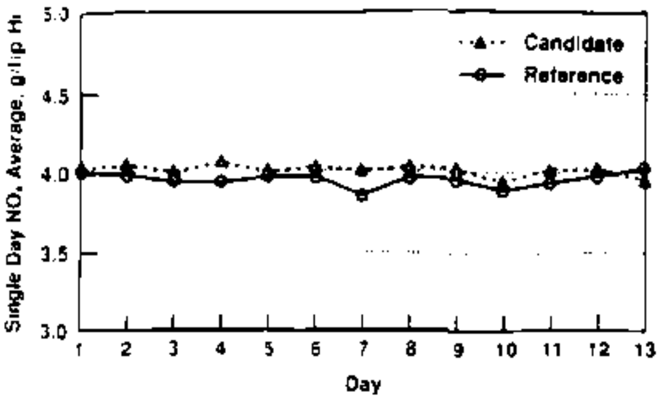

Figure 5 - CARB Diesel Qualification Test, Fuel F2 (19/59/200)

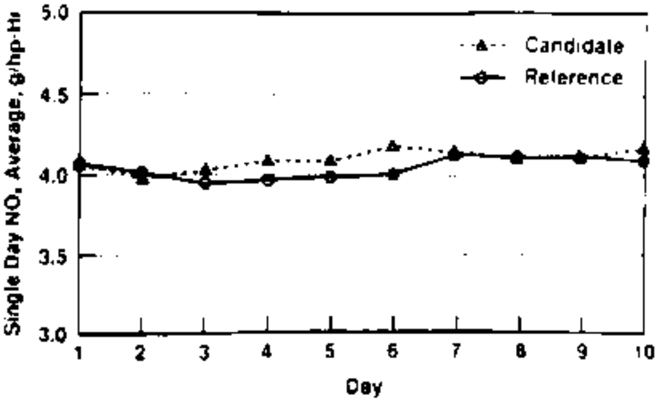

Figure 6 - CARB Diesel Qualification Test, Fuel G2 (15/55/200)

Fuel F2 was designed to be very similar to the first certified fuel with the exception of the sulfur level being around 200 ppm. This fuel passed narrowly. In order to demonstrate how close test results from the reference and the candidate fuels are, we plotted the single-day NO_x results of this test in Figure 5. The goal was to design fuels which would pass the certification test yet be as economic as possible to produce. For NO_x, there was very little "give-away" in properties in all cases where we passed the test. There was substantial "give-away" for the other four emissions measured.

Although Fuel F2's aromatics and sulfur levels are of practical use to most refineries, its high cetane number, 59, was of some concern to refineries which process crude types that yield diesel fuel with a low natural cetane number. If the cetane number is too low it cannot be raised to 59 regardless of the amount of cetane improver used. Excessive amounts of cetane improver would also increase the production cost of the fuel significantly. Fuel G2 with lower cetane number and aromatics, was formulated as an alternative and tested. It too passed the NO_x requirements narrowly as demonstrated in Figure 6. Applying the equivalency criterion, this fuel passed the NO_x requirement by only 0.12%.

Successful certification of Fuels F2 and G2 will give refineries the flexibility of producing either a higher aromatics/higher cetane number fuel or a lower aromatics/lower cetane number fuel.

COST-EFFECTIVENESS

Having succeeded in defining fuels equivalent to the CARB-defined 10% aromatics reference fuel, we are now in a position to do a rough estimate of the relative cost-effectiveness of alternative emissions reduction strategies.

The ongoing National Petroleum Council (NPC) study (11) has estimated the added cost to produce CARB (10% aromatics) diesel fuel, above and beyond the cost of the .05 wt% sulfur diesel required by the EPA regulation, at 10¢/gal. As a starting point for this estimate, the NPC study assumes a cetane number of 45 and an aromatics content of 30 vol %, as representative of a typical U.S. diesel fuel. This cost estimate is in reasonable agreement with an earlier published estimate of 13¢/gal. (12).

The cost to produce diesel fuel meeting the compositional constraints which this study has demonstrated provide equivalent NO_x emissions (and superior PM, HC, and CO emissions) to CARB's reference fuel, which will be somewhat refinery-specific. However, it is nonetheless possible to estimate that cost by assuming a fuel blending strategy which many refiners are likely to find attractive. This approach would involve producing a true 10% aromatics fuel, blending it with conventional low sulfur diesel to achieve the target aromatics level, and then treating that mixture with cetane improver to achieve the target cetane number.

Assuming that the conventional low sulfur diesel has an aromatics content equal to the NPC study baseline of 30%, hitting the target aromatics level of 19% would require a blend of 55% low aromatics stock and 45% low sulfur stock. Using the NPC estimate of 10¢/gal. for the 10% aromatics stock, the incremental cost of this blend would be 5¢/gal.

We estimate that the base cetane number of this blend would be about 48, and for this case the final cetane target is 58 to 59. Although this varies a great deal from fuel to fuel, commercial cetane improvers typically require a treat rate of 0.3 vol % to achieve a 10-number increase (13). At current market prices, this treat rate would cost about 1.5¢/gal.

The total incremental cost of the alternative diesel is then 7¢/gal. (5.5+1.5), using the assumed blending strategy. Since the NO_x emissions of the alternative are equivalent to those produced by the reference fuel, the relative NO_x cost-effectiveness is just the ratio of the two costs 7/10 = 0.7. Thus, the alternative is 30% more cost-effective than 10% aromatics diesel for NO_x alone. If credit is taken for the additional emissions reductions yielded by the alternative formula (>10% lower SOF, >30% lower HC, >20% lower CO) relative to the reference fuel, the cost-effectiveness of the alternative is even more attractive.

A final point worth re-emphasizing is that cetane improvement yields substantial reductions in HC and CO emissions: *benefits which are not realized in a NO_x reduction* strategy based on aromatics reduction.

SUMMARY

A research program was carried out by Chevron Research and Technology Company to evaluate the effects of diesel fuel properties on heavy-duty engine emissions in order to formulate alternative fuels which comply with the California low aromatics diesel regulations. Data were generated at the chassis dynamometer facility at CRTC using a heavy-duty vehicle equipped with a 1991 DDC Series 60 engine. Fuel certification tests were conducted at SwRI using a similar engine.

The effects of a number of fuel properties on emissions were investigated to identify less costly alternatives to *aromatics reduction. These included:*

1. Lowering the end point of the boiling range;
2. Using a cetane-improved commercial fuel;
3. Using an oxygenated component;
4. Adjusting the fuel viscosity;
5. Using a cetane-improved jet fuel.

Since none of the above measures resulted in formulating a CARB certifiable fuel, a statistically designed five-fuel test matrix was designed to study the effects of varying fuel aromatics content and cetane number simultaneously, within practical ranges. NO_x emissions from fuels with a range of aromatics, 13% to 19%, and cetane number, 50 to 58, were mapped. A model based on these two properties was developed. Additional tests were carried out *to relate the emissions of these five fuels to those of* a CARB reference fuel.

A total of five fuels were formulated based on the results of this research and tested at SwRI for CARB certification. Three fuels passed the tests enabling Chevron to be the first to receive CARB certification for an alternative diesel fuel.

It is important to note that data in this study were generated using one *engine* at CRTC and a *similar engine* at SwRI. This type of engine represents the type approved by CARB for fuel certification testing. Other types of heavy-duty engines may exhibit a different fuel/engine interaction but were not investigated in this study.

CONCLUSIONS

1. In this study NOx equivalency was the most difficult parameter in the CARB alternative rule to satisfy.

2. Adjusting fuel properties other than aromatics was not enough to reduce the exhaust emissions sufficiently to enable a fuel to become a potential candidate for CARB *qualification*.

3. Lowering the end point of the fuel's boiling range from 330°C (625°F) to 316°C (600°F) did not affect its NO_x emissions.

4. Currently produced Los Angeles reformulated Chevron *Special Diesel Fuel*, with up to 0.6 wt% cetane improver added, could not be improved sufficiently for CARB certification.

5. Jet fuel additized with 0.6 wt% cetane improver lowered NO_x, PM, and SOF but the reductions were not sufficient to attempt the qualification test.

6. The use of an oxygenate blend component increased NO_x by over 3%. PM and CO were each reduced by about 18%.

7. Increasing viscosity from 3.7 to 4.13 cSt by front-end distillation adjustment directionally increased NO_x, PM and CO, and directionally reduced HC. However, none of these effects was sufficient to attempt to qualify the fuel for certification.

8. Both aromatics and cetane number affect NO_x emissions significantly. Therefore, in addition to a high cetane number, and in order to certify a fuel, the aromatics content of the fuel must be reduced substantially below the current commercial levels.

9. HC and CO emissions benefits, relative to the CARB reference fuel, were significant in all cases, including fuels which failed the certification test.

10. Successful certification of a 19% aromatics, 59 cetane number fuel, and a 15% aromatics, 55 cetane number *fuel*, will *give* a *refinery* the *much* needed flexibility of producing either a higher aromatics/higher cetane number fuel or a lower aromatics/lower cetane fuel.

ACKNOWLEDGMENT

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APPENDIX I

Table I-1

SwRI - Phase A

	Hot-Start Emissions, g/bhp-Hr										BSFC Lb/bhp-Hr		Actual Work bhp-Hr	
	NO$_x$		Particulate Matter		SOF		HC		CO					
	A	P	A'	P	A'	P	A	P	A	P	A	P	A	P
03.21.91	4.10	3.38	0.176	0.138	0.0507	0.0546	0.146	0.111	1.26	1.11	0.392	0.397	22.24	21.87
	4.16	3.97	0.177	0.136	0.0505	0.0551	0.151	0.135	1.34	1.12	0.399	0.387	22.24	21.86
		3.94		0.137		0.0580		0.12		1.16		0.391		21.84
		3.93		0.131		0.0538		0.124		1.11		0.394		21.99
03.22.91	4.269	3.868	0.168	0.134	0.0687	0.0328	0.141	0.120	1.254	1.047	0.401	0.382	22.21	22.11
	4.168	3.919	0.166	0.137	0.0568	0.0344	0.161	0.125	1.311	1.126	0.399	0.387	22.15	22.08
	4.141		0.168		0.0370		0.14		1.27		0.398		22.15	
	4.229		0.167		0.0374		0.151		1.293		0.392		22.15	

Table I-2

CRTC - Phase B (Week 1)

			Hot-Start Emissions, g/bhp-Hr					BSFC, Lb/bhp-Hr	
Fuel I.D.		Work, bhp-Hr	CO	NO$_x$	HC	PM	SOF	Carbon	Gravimetric
D 4342	A	21.89	1.66	5.56	0.09	0.097	0.041	0.40	0.42
D 4342	A	21.86	1.68	5.54	0.06	0.098	0.047	0.39	0.41
D 4342	A	21.84	1.67	5.59	0.05	0.099	0.041	0.39	0.39
D 4342	A	21.81	1.65	5.62	0.05	0.099	0.040	0.38	0.42
D 4631	A*	21.87	1.73	5.38	0.06	0.092	0.035	0.40	0.41
D 4631	A*	21.83	1.75	5.42	0.05	0.097	0.037	0.40	0.40
D 4631	A*	21.82	1.71	5.44	0.05	0.093	0.038	0.39	0.38
D 4631	A*	21.85	1.65	5.37	0.04	0.092	0.036	0.39	0.41
D 4630	A'	22.00	1.50	5.38	0.03	0.087	0.034	0.39	0.40
D 4630	A'	21.90	1.55	5.37	0.05	0.088	0.034	0.39	0.40
D 4630	A'	21.93	1.54	5.21	0.06	0.091	0.037	0.38	0.37
D 4630	A'	21.87	1.53	5.21	0.04	0.089	0.036	0.38	0.37
D 4632	P	21.57	1.43	4.87	0.03	0.076	0.033	0.38	0.38
D 4632	P	21.54	1.37	4.70	0.05	0.075	0.034	0.37	0.38
D 4632	P	21.33	1.51	4.78	0.05	0.078	0.030	0.38	0.39
D 4632	P	21.46	1.47	4.70	0.05	0.078	0.033	0.37	0.41

Table I-3

CRTC - Phase B (Week 2)

Fuel I.D.		Work, bhp-Hr	Hot-Start Emissions, g/bhp-Hr					BSFC, Lb/bhp-Hr	
			CO	NO_x	HC	PM	SOF	Carbon	Gravimetric
D 4631	A*	21.76	1.67	5.25	0.05	0.090	0.028	0.38	0.39
D 4631	A*	21.94	1.50	5.19	0.07	0.086	0.031	0.38	0.38
D 4631	A	21.93	1.48	5.20	0.04	0.084	0.030	0.38	0.40
D 4631	A*	21.87	1.47	5.20	0.04	0.085	0.029	0.38	0.37
D 4342	A	21.83	1.60	5.45	0.08	0.063	0.033	0.38	0.39
D 4342	A	21.82	1.62	5.46	0.07	0.086	0.030	0.38	0.39
D 4342	A	21.77	1.65	5.42	0.06	0.086	0.029	0.38	0.39
D 4342	A	21.77	1.65	5.42	0.05	0.090	0.031	0.38	0.43
D 4632	P	21.94	1.54	4.88	0.04	0.073	0.029	0.38	0.40
D 4632	P	21.47	1.56	4.89	0.04	0.074	0.031	0.38	0.42
D 4632	P	21.43	1.53	4.96	0.03	0.074	0.036	0.38	0.41
D 4632	P	21.43	1.54	4.95	0.03	0.075	0.028	0.38	0.41
D 4630	A'	21.65	1.88	5.58	0.05	0.099	0.030	0.39	0.46
D 4630	A'	21.61	1.90	5.63	0.05	0.100	0.031	0.39	0.42
D 4630	A'	21.78	1.70	5.54	0.04	0.093	0.032	0.39	0.41
D 4630	A'	21.76	1.73	5.48	0.04	0.095	0.033	0.39	0.41

Table I-4

CRTC - Phase B (Week 3)

Fuel I.D.		Work, bhp-Hr	Hot-Start Emissions, g/bhp-Hr					BSFC, Lb/bhp-Hr	
			CO	NO_x	HC	PM	SOF	Carbon	Gravimetric
D 4630	A'	21.83	1.59	5.36	0.04	0.083	0.026	0.39	0.40
D 4630	A'	21.81	1.56	5.32	0.03	0.083	0.028	0.38	0.40
D 4342	A	21.73	1.69	5.49	0.04	0.093	0.033	0.39	0.40
D 4342	A	21.63	1.73	5.51	0.04	0.097	0.034	0.39	0.41
D 4631	A*	21.75	1.62	5.49	0.02	0.067	0.024	0.39	0.40
D 4631	A*	21.69	1.64	5.51	0.03	0.068	0.025	0.39	0.40
D 4631	A*	21.66	1.68	5.50	0.03	0.093	0.035	0.39	0.40
D 4631	A*	21.67	1.69	5.50	0.03	0.097	0.038	0.39	0.41
D 4632	P	21.49	1.52	4.87	0.03	0.076	0.032	0.37	0.42
D 4632	P	21.38	1.57	4.91	0.03	0.078	0.032	0.37	0.41

Table I-5

CRTC - Phase B (Week 4)

Fuel I.D.		Work, bhp-Hr	Hot-Start Emissions, g/bhp-Hr					BSFC, Lb/bhp-Hr	
			CO	NO_x	HC	PM	SOF	Carbon	Gravimetric
D 4632	P	21.39	1.63	5.22	0.03	0.076	0.037	0.39	0.43
D 4632	P	21.34	1.62	5.14	0.03	0.079	0.034	0.39	0.43
D 4632	P	21.33	1.64	5.23	0.03	0.080	0.037	0.39	0.43
D 4632	P	21.35	1.63	5.26	0.02	0.081	0.034	0.38	0.43
D 4630	A'	21.69	1.82	5.60	0.05	0.099	0.034	0.40	0.41
D 4630	A'	21.62	1.80	5.67	0.04	0.101	0.036	0.40	0.44
D 4630	A	21.60	1.84	5.68	0.04	0.102	0.038	0.40	0.40
D 4630	A	21.60	1.86	5.66	0.04	0.106	0.040	0.40	0.44
D 4631	A*	21.69	1.72	5.55	0.03	****	****	0.39	0.42
D 4631	A*	21.68	1.75	5.49	0.04	****	****	0.39	0.41
D 4631	A*	21.63	1.72	5.48	0.04	****	****	0.39	0.43
D 4631	A*	21.58	1.76	5.56	0.03	****	****	0.39	0.43
D 4342	A	21.73	1.75	5.56	0.05	****	****	0.39	0.42
D 4342	A	21.66	1.79	5.40	0.04	****	****	0.39	0.44
D 4342	A	21.62	1.61	5.38	0.07	****	****	0.39	0.41
D 4342	A	21.61	1.67	5.47	0.08	****	****	0.40	0.41

Table I-6

CRTC - Phase C

Fuel I.D.		Work, bhp-Hr	Hot-Start Emissions, g/bhp-hr					BSFC, Lb/bhp-Hr	
			CO	NO_x	HC	PM	SOF	Carbon	Gravimetric
D 4630	A'	21.75	1.60	5.40	0.04	0.087	0.035	0.38	0.39
D 4630	A'	21.75	1.63	5.56	0.04	0.090	0.036	0.39	0.39
D 4670	B*	21.71	1.59	5.56	0.04	0.085	0.033	0.40	0.38
D 4670	B*	21.70	1.63	5.55	0.04	0.091	0.036	0.39	0.39
D 4670	B*	21.60	1.72	5.48	0.04	0.093	0.031	0.40	0.41
D 4670	B*	21.53	1.75	5.39	0.04	0.096	0.033	0.40	0.41
D 4630	A'	21.61	1.85	5.51	0.03	0.098	0.032	0.39	0.40
D 4630	A'	21.56	1.88	5.54	0.03	0.101	0.033	0.39	0.37
D 4670	B*	21.62	1.60	5.33	0.04	0.085	0.029	0.39	0.41
D 4670	B*	21.65	1.53	5.31	0.04	0.084	0.030	0.38	0.40
D 4630	A'	21.58	1.96	5.67	0.03	0.103	0.030	0.40	0.41
D 4630	A'	21.58	1.89	5.65	0.02	0.101	0.030	0.40	0.41
D 4630	A'	21.71	1.69	5.49	0.04	0.088	0.032	0.39	0.40
D 4670	B*	21.46		5.44	0.03	0.105	0.034	0.39	0.42
D 4670	B*	21.42	2.04	5.39	0.03	0.106	0.033	0.39	0.41

Table I-7

CRTC - Phase D

Fuel I.D.		Work, bhp-Hr	Hot-Start Emissions, g/bhp-Hr					BSFC, Lb/bhp-Hr	
			CO	NO_x	HC	PM	SOF	Carbon	Gravimetric
D 4672	C'	21.78	1.72	5.59	0.04	0.091	0.029	0.39	0.40
D 4672	C	21.73	1.73	5.59	0.06	0.090	0.029	0.39	0.40
D 4684	E	21.54	1.96	5.63	0.02	0.098	0.029	0.40	0.40
D 4684	E	21.60	1.94	5.69	0.03	0.097	0.029	0.39	0.40
D 4684	E	21.59	1.98	5.71	0.08	0.074	0.021	0.40	0.41
D 4684	E	21.52	1.97	5.69	0.05	0.100	0.029	0.41	0.41
D 4672	C'	21.64	2.14	5.71	0.02	0.107	0.027	0.40	0.41
D 4672	C'	21.59	2.14	5.75	0.03	0.108	0.029	0.40	0.41
D 4684	E	21.61	1.96	5.76	0.04	0.097	0.027	0.40	0.40
D 4684	E'	21.54	1.98	5.75	0.04	0.104	0.031	0.40	0.40
D 4672	C	21.65	2.06	5.78	0.05	0.106	0.029	0.40	0.40
D 4672	C'	21.63	2.07	5.77	0.04	0.105	0.030	0.40	0.41
D 4672	C'	21.66	1.99	5.73	0.03	0.101	0.030	0.41	0.41
D 4672	C'	21.61	2.01	5.72	0.04	0.104	0.031	0.41	0.41
D 4684	E'	21.49	2.11	5.69	0.04	0.107	0.032	0.41	0.41
D 4684	E'	21.43	2.14	5.69	0.04	0.111	0.033	0.40	0.41

Table I-8

CRTC - Phase E

Fuel I.D.		Work, bhp-Hr	Hot-Start Emissions, g/bhp-Hr					BSFC, Lb/bhp-Hr	
			CO	NO_x	HC	PM	SOF	Carbon	Gravimetric
D 4672	C'	21.63	2.15	5.93	0.03	0.110	0.035	0.41	0.43
D 4672	C	21.63	2.16	5.85	0.04	0.110	0.041	0.42	0.41
D 4678	C*	21.54	2.23	5.55	0.03	0.113	0.037	0.40	0.40
D 4678	C*	21.53	2.25	5.61	****	0.112	0.031	0.40	0.40
D 4678	C*	21.65	1.90	5.75	0.03	0.096	0.029	0.40	0.41
D 4678	C*	21.61	1.89	5.77	0.03	0.097	0.032	0.40	0.40
D 4672	C'	21.64	1.98	5.82	0.02	0.099	0.030	0.40	0.40
D 4672	C'	21.62	2.00	5.86	0.02	0.101	0.031	0.40	0.40
D 4678	C*	21.72	1.88	5.96	0.02	0.096	0.032	0.41	0.41
D 4678	C*	21.67	1.90	5.85	0.03	0.097	0.032	0.40	0.40
D 4672	C	21.66	2.07	5.78	0.02	0.103	0.031	0.40	0.38
D 4672	C	21.63	2.04	5.75	0.01	0.105	0.032	0.40	0.41
D 4672	C	21.69	2.06	5.98	0.03	0.104	0.029	0.41	0.41
D 4672	C	21.68	2.02	5.80	0.03	0.103	0.030	0.40	0.41
D 4678	C*	21.56	2.17	5.81	0.03	0.081	0.022	0.40	0.40
D 4678	C*	21.51	2.19	5.83	0.03	0.109	0.029	0.39	0.40

Table I-9

CRTC - Phase F

Fuel I.D.		Work, bhp-Hr	Hot-Start Emissions, g/bhp-Hr					BSFC, Lb/bhp-Hr	
			CO	NO_x	HC	PM	SOF	Carbon	Gravimetric
D 4681	D	21.20	1.91	5.73	0.08	0.101	0.035	0.40	0.41
D 4681	D	21.20	1.92	5.76	0.09	0.104	0.037	0.40	0.42
D 4682	D'	21.27	1.74	5.66	0.04	0.097	0.031	0.40	0.41
D 4682	D'	21.29	1.71	5.64	0.04	0.072	0.022	0.40	0.42
D 4682	D'	21.25	1.69	5.60	0.06	****	****	0.40	0.41
D 4682	D'	21.27	1.68	5.52	0.07	0.093	0.032	0.40	0.42
D 4681	D	21.28	1.79	5.65	0.06	0.093	0.036	0.39	0.41
D 4681	D	21.28	1.93	5.65	0.08	0.097	0.035	0.39	0.38
D 4682	D'	21.27	1.68	5.72	0.05	0.094	0.045	0.40	0.41
D 4682	D'	21.26	1.73	5.68	0.06	0.095	0.037	0.40	0.41
D 4681	D	21.28	2.02	5.86	0.05	0.132	0.034	0.40	0.41
D 4681	D	21.29	2.01	5.84	0.07	0.106	0.036	0.41	0.41
D 4681	D	21.24	1.99	6.07	0.09	0.105	0.037	0.41	0.42
D 4681	D	21.22	2.00	5.99	0.08	0.102	0.036	0.41	0.41
D 4682	D'	21.27	1.76	5.73	0.07	0.096	0.033	0.40	0.41
D 4682	D'	21.22	1.76	5.82	0.06	0.097	0.034	0.41	0.41

Table I-10

CRTC - Phase G

Fuel I.D.		Work, bhp-Hr	Hot-Start Emissions, g/bhp-Hr					BSFC, Lb/bhp-Hr	
			CO	NO_x	HC	PM	SOF	Carbon	Gravimetric
D 4696	F'	21.23	2.08	5.79	****	****	****	0.41	0.44
D 4696	F'	21.33	1.88	5.85	0.07	0.098	0.045	0.41	0.42
D 4672	C'	21.25	2.25	5.71	0.04	0.117	0.032	0.41	0.42
D 4672	C'	21.36	2.27	5.65	0.05	0.121	0.031	0.40	0.41
D 4672	C'	21.31	2.15	5.83	0.04	0.112	0.029	0.41	0.42
D 4672	C'	21.32	2.17	5.80	0.05	0.116	0.031	0.41	0.42
D 4696	F'	21.28	1.85	5.96	0.04	0.087	0.029	0.41	0.43
D 4696	F'	21.28	1.85	5.91	0.04	0.089	0.030	0.41	0.43
D 4672	C'	21.32	2.02	5.66	0.07	0.107	0.031	0.41	0.41
D 4672	C'	21.29	2.07	5.69	0.08	0.109	0.035	0.41	0.41
D 4696	F'	21.21	1.74	5.93	0.06	0.085	0.032	0.41	0.43
D 4696	F'	21.21	1.74	5.86	0.04	0.087	0.034	0.41	0.43
D 4696	F'	21.19	1.68	5.81	0.06	0.081	0.031	0.41	0.44
D 4696	F'	21.20	1.69	5.92	0.04	0.080	0.030	0.41	0.43
D 4672	C'	21.31	2.37	5.68	0.05	0.124	0.030	0.41	0.42
D 4672	C'	21.30	2.42	5.54	0.05	0.129	0.031	0.41	0.42

Table I-11

CRTC - Phase H

			Hot Start Emissions, g/bhp-Hr					BSFC, Lb/bhp-Hr	
Fuel I.D		Work, bhp-Hr	CO	NO_x	HC	PM	SOF	Carbon	Gravimetric
D 4698	G1	21.35	1.84	5.50	0.04	0.099	0.028	0.40	0.40
D 4698	G1	21.35	1.98	5.55	0.03	0.101	0.029	0.40	0.40
D 4698	G1	21.39	2.00	5.62	0.02	0.104	0.029	0.39	0.40
D 4698	G1	21.40	2.07	5.58	0.03	0.109	0.030	0.41	0.40
D 4698	G1	21.41	2.07	5.52	0.02	0.110	0.030	0.40	0.40
D 4698	G1	21.42	2.04	5.50	0.03	0.109	0.030	0.40	0.40
D 4698	G1	21.32	2.12	5.16	0.03	0.114	0.024	0.42	0.42
D 4698	G1	21.27	1.99	5.09	0.04	0.109	0.026	0.41	0.41
D 4698	G1	21.34	2.20	5.15	0.03	0.116	0.025	0.41	0.42
D 4698	G1	21.40	2.06	5.06	0.03	0.110	0.025	0.41	0.41
D 4698	G1	21.36	2.08	5.11	0.03	0.110	0.027	0.41	0.42
D 4698	G1	21.36	2.33	5.16	0.03	0.124	0.027	0.42	0.42

Tests 1-6. Before New Control
Tests 7-12. After New Control

Table I-12

CRTC - Phase I

			Hot-Start Emissions, g/bhp-Hr					BSFC, Lb/bhp-Hr	
Fuel I.D		Work, bhp-Hr	CO	NO_x	HC	PM	SOF	Carbon	Gravimetric
D 4405	J	21.22	1.51	4.81	0.02	0.086	0.028	0.38	0.38
D 4405	J	21.24	1.53	4.85	0.03	0.087	0.030	0.38	0.37
D 4819	K	21.26	1.70	4.94	0.03	0.091	0.029	0.38	0.42
D 4819	K	21.28	1.69	4.90	0.01	0.093	0.029	0.37	0.41
D 4819	K	21.22	1.66	4.92	0.02	0.110	0.023	0.37	0.37
D 4819	K	21.24	1.61	4.90	0.02	0.095	0.023	0.38	0.37
D 4405	J	21.24	1.72	4.89	0.01	0.097	0.022	0.38	0.41
D 4405	J	21.27	1.74	4.77	0.03	0.098	0.024	0.38	0.40
D 4819	K	21.28	1.83	4.91	0.02	0.099	0.020	0.38	0.42
D 4819	K	21.32	1.86	4.91	0.03	0.102	0.021	0.38	0.41
D 4405	J	21.29	1.85	5.04	0.03	0.100	0.021	0.38	0.41
D 4405	J	21.29	1.82	5.07	0.03	0.100	0.019	0.38	0.41
D 4405	J	21.23	1.54	4.89	0.01	0.091	0.03	0.38	0.40
D 4405	J	21.24	1.54	4.92	0.04	0.093	0.027	0.39	0.39
D 4819	K	21.33	1.72	4.95	0.03	0.097	0.029	0.37	0.41
D 4819	K	21.34	1.74	4.98	0.02	0.097	0.03	0.38	0.41

APPENDIX II

Table II-1

CRTC - Phase J

			Hot-Start Emissions, g/bhp-Hr					BSFC, Lb/bhp-Hr	
Fuel I D		Work, bhp-Hr	CO	NO_x	HC	PM	SOF	Carbon	Gravimetric
D 4778	C2	21.30	1.89	4.63	0.04	0.097	0.024	0.40	0.40
D 4779	D2	21.30	1.88	4.79	0.05	0.097	0.025	0.40	0.37
D 4781	A2	21.33	1.88	4.88	0.04	0.097	0.048	0.40	0.38
D 4781	A2	21.25	1.67	4.73	0.02	0.088	0.025	0.39	0.42
D 4777	B2	21.25	1.70	4.68	0.04	0.084	0.023	0.39	0.40
D 4780	E2	21.34	1.82	5.11	0.04	0.092	0.033	0.39	0.40
D 4780	E2	21.28	1.71	4.93	0.03	0.092	0.027	0.40	0.41
D 4777	B2	21.26	1.71	4.75	0.04	0.088	0.025	0.40	0.41
D 4779	D2	21.30	1.83	5.03	0.03	0.093	0.026	0.40	0.38
D 4779	D2	21.30	1.80	4.66	0.04	0.095	0.025	0.40	0.41
D 4781	A2	21.30	1.84	4.91	0.03	0.097	0.024	0.41	0.41
D 4780	E2	21.32	1.93	4.95	0.04	0.103	0.027	0.40	0.37
D 4780	E2	21.25	1.69	4.86	0.03	0.090	0.022	0.40	0.40
D 4779	D2	21.29	1.68	4.80	0.03	0.086	0.023	0.39	0.40
D 4778	C2	21.35	1.74	4.69	0.03	0.088	0.022	0.39	0.40
D 4778	C2	21.29	1.76	4.86	0.05	0.092	0.024	0.41	0.41
D 4781	A2	21.30	1.76	4.86	0.03	0.092	0.024	0.40	0.37
D 4780	E2	21.32	1.93	5.02	0.02	0.099	0.025	0.40	0.40
D 4780	E2	21.30	1.61	4.91	0.03	0.066	0.018	0.40	0.40
D 4778	C2	21.26	1.54	4.73	0.03	0.082	0.025	0.39	0.40
D 4777	B2	21.33	1.72	4.93	0.04	0.087	0.024	0.39	0.40
D 4777	B2	21.24	1.63	4.86	0.03	0.088	0.024	0.41	0.40
D 4779	D2	21.32	1.62	4.99	0.02	0.085	0.022	0.39	0.37
D 4778	C2	21.35	1.69	4.75	0.03	0.086	0.021	0.40	0.40
D 4778	C2	21.26	1.64	4.60	0.03	0.088	0.023	0.40	0.41
D 4781	A2	21.29	1.73	4.86	0.02	0.094	0.024	0.40	0.41
D 4777	B2	21.30	1.80	4.93	0.03	0.095	0.024	0.40	0.40
D 4777	B2	21.24	1.72	4.91	0.02	0.095	0.024	0.40	0.41
D 4779	D2	21.32	1.78	4.84	0.03	0.094	0.023	0.40	0.37

Table II-1

CRTC - Phase J
(continued)

Fuel I.D.		Work, bhp-Hr	Hot-Start Emissions, g/bhp-Hr					BSFC, Lb/bhp-Hr	
			CO	NO_x	HC	PM	SOF	Carbon	Gravimetric
D 4781	A2	21.36	1.94	5.10	0.02	0.099	0.023	0.40	0.40
D 4778	C2	21.24	1.63	4.48	0.04	0.086	0.025	0.39	0.40
D 4780	E2	21.28	1.75	4.95	0.05	0.091	0.025	0.40	0.42
D 4777	B2	21.33	1.77	5.03	0.04	0.092	0.025	0.39	0.37
D 4777	B2	21.27	1.71	4.81	0.04	0.090	0.025	0.38	0.41
D 4779	D2	21.29	1.72	4.88	0.03	0.091	0.026	0.39	0.37
D 4781	A2	21.31	1.73	4.90	0.03	0.091	0.025	0.39	0.40
D 4781	A2	21.23	1.66	4.92	0.03	0.088	0.024	0.38	0.41
D 4778	C2	21.25	1.65	4.75	0.03	0.084	0.022	0.40	0.40
D 4780	E2	21.32	1.80	5.04	0.03	0.094	0.022	0.39	0.41
D 4780	E2	21.20	1.69	5.01	0.04	0.090	0.027	0.38	0.40
D 4779	D2	21.28	1.65	4.94	0.03	0.085	0.023	0.39	0.39
D 4777	B2	21.30	1.71	4.83	0.04	0.086	0.023	0.38	0.40
D 4777	B2	21.22	1.67	4.72	0.03	0.086	0.025	0.38	0.42
D 4781	A2	21.27	1.74	4.86	0.03	0.091	0.026	0.40	0.40
D 4778	C2	21.32	1.77	4.88	0.04	0.087	0.022	0.38	0.38
D 4778	C2	21.24	1.66	4.69	0.01	0.087	0.022	0.38	0.41
D 4781	A2	21.28	1.77	4.88	0.02	0.092	0.025	0.38	0.40
D 4779	D2	21.33	1.83	4.81	0.02	0.092	0.023	0.38	0.40
D 4779	D2	21.23	1.69	4.88	0.03	0.088	0.021	0.38	0.41
D 4780	E2	21.31	1.67	5.16	0.03	0.087	0.021	0.37	0.40
D 4778	C2	21.33	1.70	4.81	0.02	0.086	0.018	0.38	0.36
D 4778	C2	21.26	1.52	4.79	0.04	0.081	0.027	0.37	0.41
D 4779	D2	21.25	1.81	4.87	0.01	0.084	0.025	0.40	0.40
D 4777	B2	21.29	1.71	4.98	0.03	0.088	0.024	0.40	0.38
D 4777	B2	21.30	1.65	4.91	0.04	0.094	0.022	0.38	0.40
D 4781	A2	21.36	1.73	5.04	0.03	0.089	0.017	0.41	0.40
D 4780	E2	21.36	1.79	5.05	0.03	0.092	0.019	0.40	0.40
D 4780	E2	21.23	1.66	4.96	0.03	0.091	0.023	0.41	0.38
D 4779	D2	21.25	1.64	4.84	0.02	0.086	0.022	0.38	0.40
D 4781	A2	21.34	1.81	4.90	0.02	0.092	0.018	0.40	0.40

Table II-2

CRTC - Phase K (Reference)

Fuel I.D.		Work, bhp-Hr	Hot-Start Emissions, g/bhp-Hr					BSFC, Lb/bhp-Hr	
			CO	NO_x	HC	PM	SOF	Carbon	Gravimetric
D 4795	R2	21.31	1.99	4.91	0.03	0.104	0.024	0.37	0.37
D 4778	C2	21.27	1.81	4.73	0.02	0.090	0.022	0.39	0.40
D 4780	E2	21.37	2.01	4.92	0.03	0.101	0.022	0.38	0.40
D 4780	E2	21.31	1.93	4.91	0.04	0.100	0.024	0.38	0.41
D 4795	R2	21.36	2.09	5.07	0.03	0.109	0.025	0.39	0.41
D 4778	C2	21.34	1.85	4.88	0.02	0.089	0.021	0.38	0.37
D 4795	R2	21.31	1.84	4.88	0.02	0.097	0.026	0.39	0.40
D 4780	E2	21.32	1.76	4.92	0.03	0.092	0.026	0.39	0.40
D 4778	C2	21.35	1.72	4.70	0.02	0.087	0.024	0.38	0.40
D 4778	C2	21.26	1.64	4.66	0.03	0.086	0.025	0.39	0.40
D 4780	E2	21.92	1.73	4.79	0.03	0.091	0.028	0.38	0.39
D 4795	R2	21.34	1.99	5.09	0.03	0.104	0.027	0.39	0.41

APPENDIX III

Table III-1

SwRI - Fuel E2 (19/50)

	Hot-Start Emissions, g/bhp-Hr										BSFC, lb/bhp-Hr		Actual Work, bhp-Hr		Ret Work bhp-Hr
	NO$_x$		Part. Matter		SOF		HC		CO						
	R	E2	R	E2	R	E2	R	E2	R	E2	R	E2	R	E2	
11-21-91	4.026	4.159	0.153	0.147	0.050	0.054	0.200	0.193	1.496	1.506	0.387	0.382	22.80	22.56	23.39
	3.909	4.160	0.164	0.152	0.050	0.061	0.193	0.185	1.499	1.515	0.393	0.383	22.71	22.65	23.39
11-22-91	3.936	4.056	0.162	0.158	0.058	0.056	0.190	0.197	1.536	1.358	0.390	0.390	22.64	22.43	23.39
	3.961	4.040	0.163	0.153	0.052	0.051	0.197	0.184	1.543	1.430	0.395	0.389	22.54	22.59	23.39
11-25-91	4.015	4.116	0.158	0.137	0.045	0.046	0.192	0.175	1.442	1.335	0.389	0.379	22.46	22.33	23.39
	3.982	4.163	0.152	0.139	0.050	0.041	0.196	0.203	1.502	1.345	0.382	0.379	22.59	22.55	23.39
11-26-91	3.871	4.190	0.157	0.149	0.046	0.047	0.199	0.170	1.532	1.387	0.39	0.39	22.7	22.6	23.99
	3.974	4.101	0.166	0.145	0.046	0.048	0.172	0.170	1.486	1.391	0.39	0.39	22.5	22.6	23.39

Mean	3.959	4.126	0.159	0.148	0.050	0.051	0.192	0.185	1.505	1.408	0.391	0.384	22.586	22.544
SDEV	0.052	0.057	0.005	0.007	0.004	0.006	0.009	0.012	0.033	0.070	0.003	0.004	0.092	0.110
CV %	1.32	1.37	3.20	4.61	8.46	12.48	4.63	6.72	2.18	4.95	0.84	1.09	0.41	0.49
E2 is	4.22% Higher		6.92% Lower		2.0% Higher		3.65% Lower		6.44% Lower		Than R			

Table III-2

SwRI - Fuel A2 (19/58)

	Hot-Start Emissions, g/bhp-Hr										BSFC Lb/bhp-Hr		Actual Work bhp-Hr		Ref. Work bhp-Hr
	NO_x		Part. Matter		SOF		HC		CO						
	R	A2	R	A2	R	A2	R	A2	R	A2	R	A2	R	A2	
12/03/91	3.996	4.044	0.154	0.146	0.041	0.032	0.191	0.127	1.445	1.100	0.393	0.392	22.19	22.38	22.33
	3.963	4.002	0.154	0.148	0.045	0.034	0.195	0.124	1.503	1.103	0.390	0.397	22.48	22.35	22.33
12/04/91	3.987	3.969	0.150	0.145	0.047	0.041	0.194	0.130	1.460	1.163	0.393	0.386	22.36	22.37	22.33
	4.004	4.045	0.155	0.144	0.044	0.038	0.187	0.121	1.576	1.219	0.390	0.387	22.45	22.34	22.33
12/05/91	3.965	3.868	0.163	0.156	0.047	0.033	0.206	0.114	1.517	1.092	0.390	0.384	22.60	22.45	22.33
	3.950	4.071	0.163	0.161	0.051	0.050	0.186	0.124	1.533	1.177	0.385	0.388	22.26	22.36	22.33
12/06/91	3.981	4.078	0.153	0.151	0.036	0.041	0.175	0.124	1.502	1.097	0.387	0.376	22.04	22.21	22.33
	3.922	3.963	0.165	0.163	0.043	0.044	0.173	0.118	1.516	1.178	0.394	0.391	22.39	22.45	22.33
12/09/91	3.891	3.919	0.158	0.156	0.043	0.041	0.176	0.098	1.478	1.048	0.382	0.372	22.43	22.25	22.33
	3.984	3.905	0.160	0.157	0.045	0.031	0.173	0.103	1.502	1.169	0.390	0.391	22.49	22.23	22.33
12/10/91	3.977	3.985	0.151	0.152	0.036	0.043	0.173	0.126	1.451	1.169	0.383	0.387	22.28	22.26	22.33
	3.936	4.031	0.158	0.162	0.058	0.047	0.182	0.107	1.431	1.176	0.380	0.379	22.74	22.17	22.33
12/11/91	3.931	4.062	0.160	0.156	0.047	0.049	0.199	0.076	1.503	1.077	0.384	0.371	22.34	22.46	22.33
	3.910	3.996	0.171	0.159	0.061	0.045	0.158	0.096	1.465	1.137	0.394	0.394	22.53	22.54	22.33
12/12/91	3.993	4.056	0.166	0.157	0.056	0.052	0.141	0.095	1.494	1.143	0.382	0.384	22.70	22.33	22.33
	4.010	4.028	0.161	0.159	0.045	0.049	0.163	0.089	1.543	1.146	0.382	0.388	22.45	22.30	22.33
12/13/91	3.974	3.993	0.161	0.160	0.036	0.032	0.170	0.112	1.485	1.152	0.386	0.387	22.45	22.40	22.33
	3.894	3.953	0.169	0.158	0.044	0.038	0.194	0.118	1.453	1.100	0.378	0.375	22.32	22.37	22.33
12/16/91	3.980	4.021	0.155	0.157	0.034	0.031	0.185	0.127	1.357	1.038	0.373	0.378	22.39	22.47	22.33
	3.983	3.998	0.155	0.155	0.031	0.027	0.179	0.124	1.395	1.061	0.369	0.376	22.56	22.47	22.33
Mean	3.9601	3.9864	0.1591	0.1552	0.0445	0.0399	0.1802	0.1127	1.4815	1.1273	0.3853	0.3842	22.443	22.399	
SDEV	0.0350	0.0640	0.0058	0.0056	0.0079	0.0075	0.0155	0.0151	0.0507	0.0498	0.0069	0.0075	0.1460	0.0990	
CV %	0.884	1.351	3.646	3.608	17.753	18.797	8.602	13.404	3.422	4.418	1.791	1.952	0.651	0.443	
A2 is	0.92% Higher		2.45% Lower		10.34% Lower		37.46% Lower		23.91% Lower		Than R				

Table III-3

SwRI - Fuel D2 (16/54)

	Hot Start Emissions g/bhp-Hr										BSFC Lb/bhp-Hr		Actual Work bhp-Hr		
	NO$_x$		Part. Matter		SOF		HC		CO						
	R	D2	R	D2	R	D2	R	D2	R	D2	R	D2	R	D2	Ref Work bhp-Hr
01/07/92	3.857	3.924	0.175	0.152	0.056	0.060	0.180	0.126	1.601	1.298	0.396	0.397	22.39	22.08	23.56
	3.941	4.085	0.160	0.154	0.034	0.030	0.203	0.110	1.627	1.263	0.401	0.407	21.99	21.98	23.56
01/08/92	3.909	3.957	0.159	0.150	0.048	0.026	0.165	0.130	1.586	1.250	0.400	0.393	22.11	22.12	23.56
	3.934	3.895	0.157	0.150	0.069	0.031	0.180	0.131	1.520	1.218	0.395	0.393	22.34	22.18	23.56
01/09/92	3.847	3.995	0.156	0.142	0.036	0.036	0.193	0.109	1.576	1.190	0.391	0.392	22.18	22.29	23.56
	3.950	4.098	0.153	0.146	0.034	0.028	0.173	0.119	1.535	1.189	0.393	0.394	22.04	22.14	23.56
01/10/92	3.981	4.018	0.153	0.151	0.036	0.041	0.175	0.124	1.502	1.097	0.387	0.376	22.34	22.21	23.56
	3.922	3.963	0.165	0.163	0.043	0.044	0.173	0.118	1.516	1.178	0.394	0.391	22.39	22.45	23.56
01/13/92	3.899	3.910	0.163	0.150	0.043	0.047	0.176	0.145	1.557	1.247	0.392	0.384	21.87	22.03	23.56
	3.917	3.854	0.174	0.159	0.060	0.031	0.191	0.141	1.578	1.213	0.389	0.388	22.20	22.09	23.56
01/14/92	3.962	3.961	0.168	0.154	0.038	0.034	0.219	0.140	1.522	1.218	0.388	0.389	22.15	22.02	23.56
	4.031	3.954	0.164	0.151	0.035	0.045	0.182	0.135	1.532	1.247	0.392	0.385	22.17	22.05	23.56
01/15/92	3.928	4.030	0.162	0.146	0.051	0.043	0.197	0.136	1.542	1.219	0.398	0.387	22.14	22.29	23.56
	3.912	3.992	0.154	0.143	0.031	0.027	0.173	0.139	1.488	1.246	0.391	0.389	22.24	22.38	23.56
01/16/92	3.905	4.021	0.148	0.139	0.047	0.044	0.167	0.178	1.500	1.248	0.392	0.388	22.15	21.92	23.56
	3.760	3.844	0.160	0.141	0.038	0.044	0.187	0.167	1.536	1.300	0.384	0.389	22.18	22.09	23.56
01/17/92	3.835	3.878	0.156	0.145	0.050	0.048	0.194	0.143	1.615	1.266	0.392	0.384	22.32	22.13	23.56
	3.894	3.904	0.158	0.148	0.053	0.053	0.163	0.138	1.628	1.321	0.385	0.394	22.20	22.16	23.56
01/20/92	3.898	3.899	0.152	0.153	0.048	0.054	0.183	0.117	1.484	1.159	0.388	0.388	22.14	22.14	23.56
	3.848	4.046	0.152	0.152	0.042	0.055	0.176	0.116	1.504	1.208	0.389	0.413	22.26	22.01	23.56
Mean	3.9008	3.9710	0.1587	0.1477	0.0458	0.0418	0.1827	0.1345	1.5385	1.2272	0.3925	0.3910	22.173	22.121	
SDEV	0.0597	0.0823	0.0073	0.0058	0.0101	0.0106	0.0145	0.0169	0.0597	0.0536	0.0047	0.0090	0.1210	0.1120	
CV %	1.530	2.073	4.600	3.927	22.052	25.359	7.937	12.565	3.880	4.368	1.197	2.302	0.546	0.506	
D2's	1.8% Higher		6.93% Lower		8.73% Higher		26.38% Lower		23.23% Lower		Than R				

Table III-4

SwRI - Fuel F2 (19/59/200)

	Hot-Start Emissions, g/bhp-hr										BSFC Lb/bhp-hr		Actual Work bhp-hr		
	NOx		Part. Matter		SOF		HC		CO						
	R	F2	R	F2	R	F2	R	F2	R	F2	R	F2	R	F2	Ref. Work bhp-hr
07/15/92	3.969	4.015	0.170	0.170	0.038	0.031	0.152	0.109	1.457	1.168	0.393	0.396	22.46	22.53	23.76
	4.055	4.061	0.172	0.170	0.037	0.027	0.168	0.102	1.485	1.163	0.397	0.400	22.37	22.53	23.76
07/16/92	3.961	4.001	0.164	0.165	0.039	0.030	0.173	0.104	1.515	1.148	0.396	0.386	22.39	22.58	23.76
	4.008	4.103	0.165	0.161	0.041	0.029	0.151	0.109	1.523	1.143	0.397	0.391	22.30	22.30	23.76
07/17/92	3.890	4.055	0.165	0.146	0.041	0.028	0.164	0.090	1.491	1.136	0.383	0.392	22.34	22.56	23.76
	4.008	3.968	0.172	0.161	0.041	0.027	0.165	0.100	1.481	1.150	0.394	0.393	22.33	22.70	23.76
07/20/92	3.977	4.093	0.170	0.175	0.049	0.042	0.169	0.134	1.487	1.100	0.392	0.393	22.33	22.41	23.75
	3.905	4.050	0.177	0.160	0.042	0.036	0.148	0.098	1.440	1.154	0.396	0.396	22.44	22.43	23.76
07/21/92	3.989	3.932	0.167	0.156	0.048	0.038	0.168	0.103	1.543	1.133	0.395	0.392	22.41	22.44	23.76
	3.961	4.057	0.169	0.170	0.041	0.039	0.144	0.102	1.448	1.164	0.396	0.393	22.61	22.43	23.76
07/22/92	4.030	4.014	0.174	0.162	0.041	0.033	0.153	0.100	1.522	1.111	0.394	0.396	22.49	22.53	23.76
	3.886	4.027	0.162	0.155	0.037	0.031	0.165	0.142	1.497	1.125	0.395	0.390	22.44	22.53	23.76
07/23/92	3.813	3.934	0.157	0.157	0.039	0.030	0.148	0.107	1.492	1.094	0.388	0.386	22.42	22.60	23.76
	3.869	4.052	0.164	0.146	0.033	0.033	0.151	0.113	1.410	1.148	0.383	0.392	22.55	22.50	23.76
07/24/92	3.966	3.985	0.167	0.162	0.042	0.058	0.163	0.107	1.477	1.114	0.388	0.397	22.58	22.39	23.76
	3.933	4.053	0.154	0.156	0.032	0.032	0.127	0.073	1.429	1.104	0.392	0.391	22.48	22.47	23.76
07/27/92	3.931	4.039	0.160	0.167	0.040	0.059	0.172	0.101	1.515	1.125	0.390	0.398	22.53	22.48	23.76
	3.951	3.970	0.156	0.164	0.036	0.031	0.140	0.089	1.479	1.125	0.399	0.393	22.52	22.50	23.76
07/28/92	3.834	3.895	0.167	0.165	0.041	0.031	0.162	0.095	1.487	1.193	0.389	0.395	22.42	22.28	23.75
	3.913	3.97	0.16	0.16	0.04	0.037	0.13	0.104	1.427	1.114	0.389	0.396	22.49	22.31	23.75
07/29/92	3.973	4.01	0.16	0.16	0.04	0.032	0.13	0.114	1.508	1.128	0.400	0.399	22.39	22.41	23.75
	3.864	3.99	0.17	0.18	0.04	0.046	0.13	0.105	1.457	1.128	0.388	0.391	22.71	22.43	23.75
07/30/92	3.974	3.93	0.16	0.18	0.04	0.038	0.14	0.094	1.499	1.111	0.394	0.395	22.36	22.48	23.76
	3.862	4.06	0.17	0.18	0.04	0.035	0.14	0.101	1.483	1.106	0.386	0.391	22.41	22.38	23.76
08/04/92	3.943	3.92	0.17	0.17	0.05	0.05	0.16	0.096	1.538	1.105	0.393	0.392	22.50	22.53	23.75
	4.086	3.96	0.17	0.17	0.05	0.028	0.14	0.105	1.443	1.083	0.385	0.388	22.55	22.48	23.75
Mean	3.9470	4.0061	0.1675	0.1645	0.0400	0.0358	0.1521	0.1037	1.4813	1.1297	0.3920	0.3931	22.455	22.477	
SDEV	0.0629	0.0571	0.0070	0.0093	0.0047	0.0088	0.0141	0.0131	0.0351	0.0261	0.0047	0.0036	0.0980	0.0890	
CV %	1.594	1.425	4.179	5.647	11.750	24.578	9.272	12.629	2.370	2.310	1.199	0.916	0.436	0.396	
F2 is	1.5% Higher		1.8% Lower		10.5% Lower		31.82% Lower		23.74% Lower		Than R				

Table III-5

SwRI - Fuel G2 (15/55/200)

	Hot-Start Emissions, g/bhp-Hr										BSFC, Lb/bhp-Hr		Actual Work bhp-Hr		
	NO$_x$		Part. Matter		SOF		HC		CO						
	R	G2	R	G2	R	G2	R	G2	R	G2	R	G2	R	G2	Ref Work bhp-Hr
12/02/92	4.111	4.046	0.157	0.140	0.049	0.044	0.152	0.113	1.425	1.216	0.380	0.378	22.55	22.53	23.59
	4.039	4.077	0.163	0.138	0.042	0.038	0.131	0.132	1.486	1.257	0.377	0.373	22.72	22.56	23.59
12/03/92	4.072	3.946	0.162	0.147	0.050	0.043	0.144	0.121	1.495	1.243	0.389	0.368	22.36	22.41	23.59
	3.949	4.006	0.171	0.148	0.038	0.033	0.130	0.111	1.486	1.208	0.385	0.375	22.57	22.38	23.59
12/04/92	3.933	4.035	0.161	0.144	0.039	0.031	0.109	0.090	1.500	1.257	0.359	0.360	22.67	22.30	23.59
	3.947	4.010	0.159	0.146	0.045	0.042	0.143	0.101	1.421	1.228	0.359	0.374	22.65	22.45	23.59
12/07/92	3.992	4.160	0.177	0.142	0.044	0.038	0.126	0.103	1.444	1.215	0.364	0.367	22.36	22.44	23.59
	3.934	4.001	0.154	0.141	0.043	0.041	0.136	0.114	1.458	1.196	0.360	0.363	22.73	22.53	23.59
12/08/92	3.951	4.113	0.153	0.136	0.047	0.044	0.096	0.123	1.449	1.156	0.342	0.367	22.62	22.49	23.59
	4.010	4.036	0.157	0.141	0.056	0.046	0.128	0.084	1.475	1.191	0.345	0.350	22.60	22.64	23.59
12/09/92	3.939	4.130	0.156	0.135	0.045	0.039	0.090	0.106	1.454	1.228	0.370	0.374	22.63	22.31	23.59
	4.051	4.222	0.168	0.137	0.035	0.029	0.121	0.104	1.559	1.345	0.373	0.385	22.76	22.21	23.59
12/10/92	4.175	4.144	0.156	0.133	0.045	0.043	0.096	0.088	1.428	1.171	0.358	0.365	22.49	22.35	23.59
	4.061	4.114	0.160	0.145	0.066	0.035	0.136	0.076	1.412	1.140	0.377	0.374	22.41	22.23	23.59
12/11/92	4.152	4.105	0.157	0.137	0.043	0.052	0.106	0.080	1.460	1.265	0.347	0.356	22.46	22.43	23.59
	4.062	4.088	0.154	0.142	0.038	0.042	0.133	0.085	1.527	1.290	0.362	0.362	22.62	22.45	23.59
12/14/92	4.096	4.109	0.154	0.148	0.051	0.039	0.114	0.087	1.447	1.219	0.377	0.343	22.59	22.35	23.59
	4.100	4.110	0.160	0.147	0.040	0.034	0.140	0.096	1.488	1.199	0.357	0.363	22.53	22.35	23.59
2/15/92	4.053	4.160	0.171	0.151	0.049	0.030	0.117	0.096	1.562	1.357	0.357	0.351	22.67	22.39	23.59
	4.093	4.15	0.17	0.15	0.04	0.035	0.11	0.094	1.639	1.375	0.355	0.357	22.57	22.37	23.59
Mean	4.0360	4.0880	0.1608	0.1423	0.0453	0.0389	0.1229	0.1002	1.4808	1.2378	0.3647	0.3653	22.578	22.409	
SDEV	0.0754	0.0677	0.0066	0.0052	0.0071	0.0059	0.0175	0.0153	0.0561	0.0638	0.0133	0.0105	0.1160	0.1080	
CV %	1.868	1.656	4.106	3.654	15.673	15.167	14.239	15.269	3.789	5.154	3.647	2.875	0.514	0.482	
G2 is	1.3% Higher		11.5% Lower		14.1% Lower		18.5% Lower		16.4% Lower		Than R				