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Elastomer Compatibility Testing of Renewable Diesel Fuels

Technical Report
NREL/TP-540-38834
November 2005

E. Frame
Southwest Research Institute

R.L. McCormick
National Renewable Energy Laboratory

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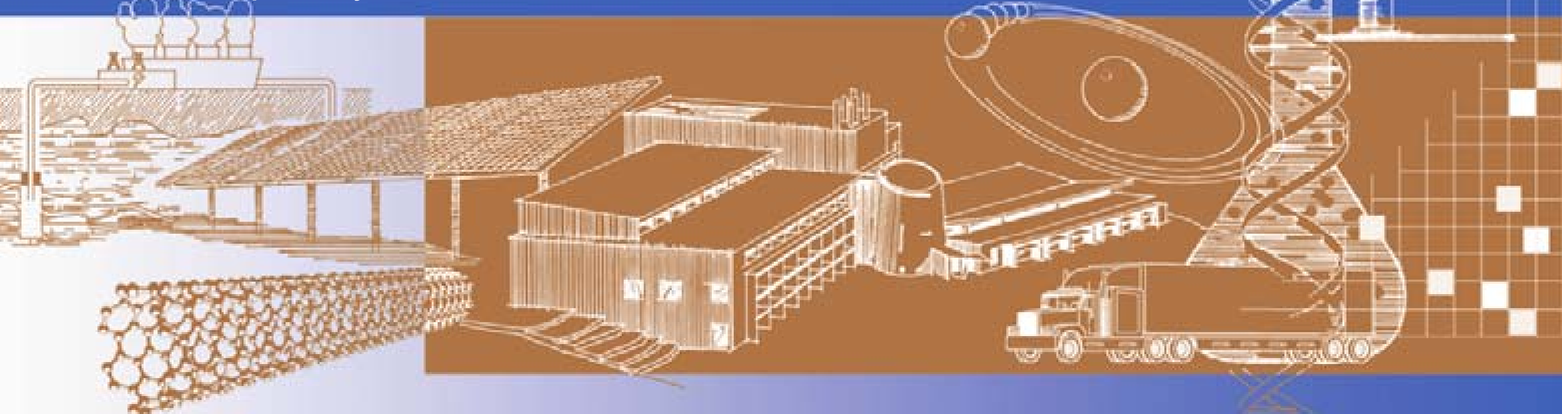

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Summary and Introduction

The U.S. Department of Energy (DOE) Fuels Technologies Program, under the DOE FreedomCAR and Vehicle Technologies Program, is charged with performing research to eliminate technical barriers to market penetration of renewable and synthetic fuels. One aspect of this program is to ensure that blends of petroleum-derived fuels and renewable fuels can be utilized without negative impact on engine durability. Materials compatibility is an important component of this research. The blending of renewable components, such as biodiesel or ethanol, into diesel fuel may impact the integrity and performance of various fuel system elastomers. The Southwest Research Institute conducted this work for the National Renewable Energy Laboratory (NREL) as part of a program to determine how ethanol and biodiesel affect these materials.

Six elastomers (N1059, N674, N0497, V747, and V884) commonly used in automotive applications were tested with the following fuels:

- Certification diesel fuel
- Certification diesel fuel blended with 15% ethanol
- Certification diesel fuel blended with 20% soy-derived biodiesel.

The elastomers were examined for thickness, diameter, and break load both before and after soaking in these fuels for 500 hours at 40°C. Additionally, a control set was exposed to dry air only for the same length of time.

The results indicate that all of these elastomers appear to be fully compatible with 20% biodiesel blends. Overall, for each elastomer type, the ethanol-containing fuel had the largest impact on elastomer properties after storage. Thus these elastomers may not be fully compatible in all applications with fuels containing 15% ethanol.

Test Details

The following fuels were included in the investigation:

1. Fuel designated CL02-576, which was a certification diesel fuel with 29.2%vol aromatics and 346 ppm sulfur. Appendix A features a certificate of analysis for this fuel.
2. Fuel CL02-577 was a blend of 15%vol ethanol and 85%vol certification diesel fuel (E15). The fuel-grade ethanol was supplied by NREL.
3. Fuel CL02-578 was a blend of 20%vol soy-biodiesel (B20) and 80%vol certification diesel fuel. The B-100 used for the blend was Soy Gold (AL-25842).
4. No fuel; a set of samples were exposed to air only and served as a baseline.

Both the biodiesel and fuel-grade ethanol met applicable ASTM standards.

The test matrix of elastomers (all tested as O-rings) included:

- N674 general purpose nitrile rubber
- N0497 high aceto-nitrile content rubber for better fuel resistance

- N1059 peroxide-cured nitrile rubber
- V747 flourocarbon filled with carbon black
- V884 flourocarbon without carbon black.

These elastomers were chosen because they were the same used in a prior study of various fuel oxygenates [1].

All elastomer tests were performed using four specimens, so any outliers could be removed based on statistics or engineering judgment. The elastomers stored in fuel were exposed for 500 hours at 40°C. The baseline samples were only exposed to ambient laboratory room temperature. The following measurements were made after storage on all samples:

- O-ring thickness
- O-ring inside diameter
- Break load
- Sample volume and tensile strength, calculated from the primary measurements.

Results

Appendix B includes raw data, data with outliers removed, calculated values, and plots. No individual sample results were dropped based on statistical considerations; however, the following three tests were removed based on engineering judgment because their break loads were unusually low:

- Sample 1 of N1059 in B20 (CL02-578)
- Sample 4 of V747 in E15 (CL02-577)
- Sample 2 of V884 in B20 (CL02-578).

It is interesting to note that no outliers were observed or rejected for elastomers soaked in the baseline diesel fuel.

Bar graphs with 95% confidence bands are presented for the following parameters in Appendix C:

- Break load
- Break stress
- O-ring inside diameter
- O-ring thickness
- O-ring volume.

The following statistically significant differences were observed within each elastomer type.

N1059 Peroxide-Cured Nitrile Rubber

The average break load and corresponding break stress were lowest when exposed to the ethanol-containing fuel. Compared to the baseline, break load was reduced by 32%. The results with baseline fuel, biodiesel, and air were not significantly different.

O-ring volume was the lowest for the samples stored in air, as well as for the samples stored in the fuels. With this elastomer, each fuel type produced the same level of swell (approximately 18% compared to the baseline).

N674 General Purpose Nitrile Rubber
The average break load and stress was the lowest for samples exposed to the ethanol-containing fuel (37% less than baseline). Similar break load and stress values were observed with the base fuel and biodiesel. Samples exposed to air had the highest break load and stress.

O-ring volume was lowest for samples exposed to air. Samples exposed to base fuel and biodiesel had the same level of increased volume (approximately 14%-18%), while the samples exposed to the ethanol-containing fuel had the largest volume increased compared to the baseline (35%).

N0497 High Aceto-Nitrile Content Rubber
Trends similar to N674 were observed. Break load was 13% lower for ethanol-exposed samples, and volume increase was 11% compared to baseline. The results with baseline fuel, biodiesel, and air were not significantly different.

V747 Flourocarbon Filled with Carbon Black
The average break load and stress were substantially lower for the samples exposed to ethanol (32% compared to baseline). O-ring volume increase was highest with the ethanol-containing fuel (7%). The results with base fuel, biodiesel, and air were the same statistically.

V884 Flourocarbon without Carbon Black
Trends similar to V747 were observed. Compared to baseline, break load was reduced by 28%, and volume increase was 10% for the fuel containing ethanol. The results with baseline fuel, biodiesel, and air were not significantly different.

Conclusions

In general the samples exposed to only air exhibited higher break load than samples exposed to any of the fuels. Samples exposed to the ethanol-diesel blend exhibited a significant reduction in break load for all elastomers except N0497. Samples exposed to B20 did not exhibit significantly different break load from those exposed to the baseline fuel. These observations are mirrored in the calculated break stress. O-ring dimensions and volume typically increase for O-rings soaked in fuel relative to the air-exposed controls. The largest increase in dimensions and volume is observed for the ethanol-diesel blends. Elastomers exposed to B20 did not exhibit significantly different dimensions or volume from those exposed to the baseline diesel fuel.

The results indicate that all of these elastomers appear to be fully compatible with 20% biodiesel blends. Overall, for each elastomer type, the fuel containing ethanol had the largest impact on elastomer properties after storage. Thus these elastomers may not be fully compatible in all applications with fuels containing 15% ethanol.

Reference

1. Natarajan, M.; González, M.A.; Frame, E.A.; Naegeli, D.W.; Liney, E.; Asmus, T.; Piel, W.; Clark, W.; Wallace III, J.P; Garbak, J. "Oxygenates for Advanced Petroleum-Based Diesel Fuels: Part 1. Screening and Selection Methodology for the Oxygenates" *Society of Automotive Engineers Technical Paper No. 2001-01-3631;* 2001.

Appendix A:
Certificate of Analysis—Diesel .05 LS Cert Fuel (#2)

Chevron Phillips Chemical Company LP

GM-4712-F

DATE OF SHIPMENT
09-05-02

CUSTOMER PO NO.
282264-S

SALES ORDER NO.
5596161

TRAILER NO. 59-83007

MFG. DATE: 08-2002

CERTIFICATE OF ANALYSIS

DIESEL .05 LS CERT FUEL (# 2)
LOT 2HP05201

TESTS	RESULTS	SPECIFICATIONS	METHOD
Specific Gravity, 60/60	0.8490	0.8398 – 0.8654	ASTM D-4052
API Gravity	35.17	32 – 36	ASTM D-1298
Corrosion, 50°C, 3 hrs	1A	3 Max	ASTM D-130
Sulfur, ppm	346	300 – 500	ASTM D-2622
Flash Point, °F	164.1	130 Min	ASTM D-93
Pour Point, °F	-10	0 Max	ASTM D-97
Cloud Point, °F	+3	Report	ASTM D-2500
Viscosity, cs 40°C	2.6	2.2 – 3.2	ASTM D-445
Carbon wt%	86.84	Report	Phillips
Hydrogen wt%	13.16	Report	Phillips
Carbon Density (gm/gal)	2785	2750 – 2806	Calculated
Net Heat of Combustion BTU/LB	18440	Report	ASTM D-3338
Particulate Matter (mg/l)	5.2	15 Max	ASTM D-2276
Cetane Index	47.3	40 – 48	ASTM D-976
Cetane Number	46.03	40 – 48	ASTM D-613
DISTILLATION, °F			**ASTM D-86**
IBP	364.9	340 – 400	
5%	405.9		
10%	427.4	400 – 460	
20%	455.5		
30%	476.3		
40%	494.7		
50%	510.1	470 – 540	
60%	526.1		
70%	543.2		
80%	562.7		
90%	587.3	560 – 630	
95%	606.7		
EP	633.1	610 – 690	
Loss	0.9		
Residue	0.5		
HYDROCARBON TYPE, VOL%			**ASTM D-1319**
Aromatics	29.2	28 – 31	
Olefins	1.0	Report	
Saturates	69.8	Report	

D.G. Doerr teh

D.G. Doerr
Fuels Unit Team Leader

DGD: teh
09/05/02

Appendix B:
Raw Data, Data with Outliers Removed, Calculated Values, and Plots

Elastomer	Fuel	Specimen ID	Inside Diameter *(in)*	Outside Diameter *(in)*	thickness O-ring Diameter *(in)*	Break Load *(lbs)*	Std dev Break Load *(lbs)*	95% C I Break Load *(lbs)*	Break Stress *(psi)*	Std dev Break Stress *(psi)*	95% C I Break Stress *(psi)*	Average Break Stress *(psi)*	Volume *(in^3)*	Average Volume *(in^3)*	95% C.I. Volume *(in^3)*
N674	CL02-576	1	1.034	1.182	0.0743	14.08			1626			1803	0.015078	0.015169	6.65E-05
		2	1.033	1.182	0.0746	16.83			1927				0.015199		
		3	1.031	1.180	0.0745	16.58	1.26	1.24	1904	140	138		0.015135		
		4	1.036	1.185	0.0746	15.36			1756				0.015262		
	CL02-577	1	1.072	1.226	0.0774	12.55			1336			1255	0.016967	0.017373	0.00026
		2	1.075	1.231	0.0782	11.83			1231				0.017415		
		3	1.068	1.227	0.0791	13.30	1.14	1.11	1353	116	113		0.017726		
		4	1.068	1.225	0.0784	10.63			1102				0.017384		
	CL02-578	1	1.029	1.177	0.0740	15.36			1785			1811	0.014916	0.014671	0.000294
		2	1.029	1.176	0.0734	15.37			1816				0.014666		
		3	1.031	1.174	0.0722	14.66	3.07	3.01	1792	28	28		0.014175		
		4	1.029	1.177	0.0740	15.91			1848				0.014926		
N0497	CL02-576	1	1.185	1.324	0.0694	12.48			1648			1598	0.014928	0.015211	0.000159
		2	1.180	1.321	0.0705	12.26			1572				0.015328		
		3	1.182	1.323	0.0703	12.22	0.12	0.12	1575	35	34		0.015269		
		4	1.188	1.329	0.0702	12.38			1598				0.015317		
	CL02-577	1	1.225	1.372	0.0734	11.28			1335			1392	0.017248	0.016466	0.000935
		2	1.225	1.372	0.0735	11.39			1343				0.017311		
		3	1.230	1.366	0.0682	11.01	0.16	0.16	1507	436	427		0.014905		
		4	1.219	1.363	0.0718	11.19			1384				0.016403		
	CL02-578	1	1.185	1.323	0.0694	11.80			1559			1570	0.014918	0.015207	0.000226
		2	1.189	1.330	0.0708	12.00			1527				0.015558		
		3	1.173	1.314	0.0705	12.49	0.31	0.30	1601	34	33		0.015247		
		4	1.175	1.315	0.0701	12.29			1592				0.015104		
N1059	CL02-576	1	1.243	1.386	0.0713	16.59			2078			1948	0.016491	0.016964	0.000456
		2	1.238	1.383	0.0730	17.36			2074				0.017239		
		3	1.242	1.385	0.0714	17.66	2.56	2.51	2206	347	341		0.016527		
		4	1.248	1.395	0.0735	12.16			1435				0.017599		
	CL02-577	1	1.282	1.429	0.0733	9.34			1106			1421	0.017993	0.01733	0.000521
		2	1.283	1.423	0.0703	12.79			1649				0.016494		
		3	1.276	1.421	0.0726	12.10	1.52	1.49	1464	227	223		0.017509		
		4	1.275	1.419	0.0722	11.99			1465				0.017325		
	CL02-578	1	1.232	1.369	0.0688	6.97			939			1798	0.015172	0.016084	0.000575
		2	1.242	1.382	0.0702	16.84			2179				0.015934		
		3	1.241	1.384	0.0715	18.15	5.00	4.90	2260	605	593		0.016567		
		4	1.238	1.382	0.0718	14.69			1815				0.016664		
V747	CL02-576	1	0.863	1.001	0.0693	13.91			1845			1854	0.011044	0.011109	0.000441
		2	0.874	1.008	0.0669	13.73			1953				0.010397		
		3	0.868	1.008	0.0702	14.51	0.36	0.35	1877	183	179		0.011394		
		4	0.863	1.005	0.0710	13.77			1742				0.011603		
	CL02-577	1	0.898	1.041	0.0718	9.88			1222			999	0.012321	0.011957	0.000233
		2	0.893	1.033	0.0700	9.41			1223				0.011643		
		3	0.900	1.041	0.0707	9.66	3.59	3.51	1232	453	444		0.011955		
		4	0.900	1.041	0.0705	2.49			319				0.011909		
	CL02-578	1	0.861	1.007	0.0731	15.02			1789			1798	0.012324	0.01169	0.00065
		2	0.854	1.001	0.0736	14.32			1685				0.012393		
		3	0.875	1.011	0.0684	13.76	0.56	0.55	1871	83	81		0.010901		
		4	0.871	1.010	0.0693	13.93			1848				0.011141		
V884	CL02-576	1	0.986	1.124	0.0688	13.21			1778			1749	0.012319	0.012571	0.000182
		2	0.981	1.120	0.0695	13.00			1712				0.012536		
		3	0.992	1.130	0.0693	13.46	0.19	0.18	1784	37	36		0.012579		
		4	0.993	1.133	0.0700	13.25			1723				0.01285		
	CL02-577	1	1.008	1.151	0.0719	10.28			1266			1215	0.013783	0.013951	0.00052
		2	1.013	1.154	0.0709	9.93			1259				0.013433		
		3	1.015	1.164	0.0743	10.10	0.37	0.36	1164	54	53		0.014856		
		4	1.015	1.158	0.0716	9.43			1173				0.013733		
	CL02-578	1	0.991	1.125	0.0668	12.82			1833			1559	0.011634	0.012267	0.00051
		2	0.987	1.127	0.0698	6.30			823				0.012721		
		3	0.988	1.123	0.0675	13.21	3.43	3.36	1848	494	484		0.01186		
		4	0.988	1.128	0.0702	13.40			1733				0.012855		
N647	Air	1	0.990	1.132	0.0708	19.4	0.11	0.11	2463	43	42.00	2495	0.013114	0.012905	0.000151
		2	0.989	1.130	0.0704	19.2			2465				0.01295		
		3	0.991	1.130	0.0696	19.4			2555				0.012678		
		4	0.990	1.130	0.0702	19.3			2496				0.012877		
N0497	Air	1	1.174	1.313	0.0695	12.9	0.54	0.53	1705	75	73.58	1696	0.014821	0.014885	3.98E-05
		2	1.169	1.308	0.0698	12.6			1651				0.014877		
		3	1.167	1.307	0.0699	12.5			1630				0.014926		
		4	1.175	1.315	0.0697	13.7			1799				0.014916		
N1059	Air	1	1.176	1.311	0.0677	19.5	2.05	2.01	2710	374	366.57	2276	0.014062	0.014629	0.000686
		2	1.168	1.303	0.0673	17.4			2444				0.013805		
		3	1.171	1.312	0.0703	14.5			1872				0.015156		
		4	1.168	1.310	0.0712	16.5			2077				0.015492		
V747	Air	1	0.865	1.005	0.0701	15.2	0.49	0.48	1968	77	75.75	1901	0.011328	0.011242	0.000124
		2	0.866	1.004	0.0692	14.7			1953				0.011052		
		3	0.864	1.004	0.0697	14.4			1886				0.011202		
		4	0.860	1.001	0.0704	14.0			1799				0.011386		
V884	Air	1	0.988	1.126	0.0687	14.4	0.65	0.64	1943	119	116.47	1818	0.012325	0.012693	0.000238
		2	0.989	1.130	0.0704	13.0			1676				0.012944		
		3	0.985	1.124	0.0696	14.3			1884				0.012615		
		4	0.992	1.132	0.0701	13.7			1768				0.012888		

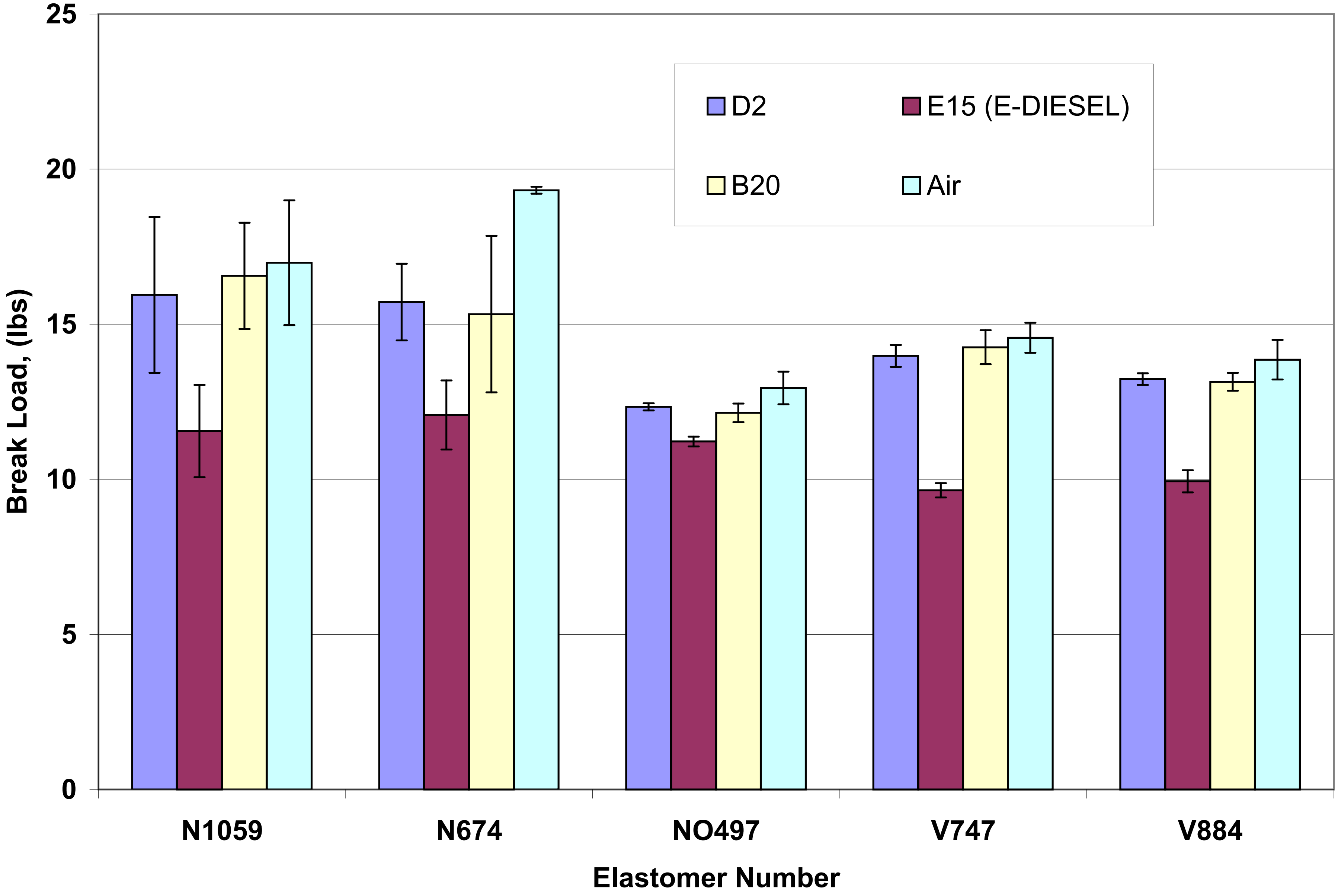
OUTLIERS

Elastomer	Fuel	Specimen ID	Inside Diameter (in)	Outside Diameter (in)	thickness O-ring Diameter (in)	Break Load (lbs)	Std dev Break Load (lbs)	95% C I Break Load (lbs)	Break Stress (psi)	Std dev Break Stress (psi)	95% C I Break Stress (psi)	Average Break Stress (psi)	Break Stress T	Volume (in^3)	Average Volume (in^3)	95% C.I. Volume (in^3)	avg id in	95%CI id in	avg thickness in	95%CI thickness in
N674	CL02-576	1	1.034	1.182	0.0743	14.08			1626				-1.26	0.015078						
		2	1.033	1.182	0.0746	16.83			1927				0.88	0.015199						
		3	1.031	1.180	0.0745	16.58	1.26	1.24	1904	140	138	1803	0.72	0.015135	0.015169	7.80268E-05	1.033	0.001661	0.074	0.000164
		4	1.036	1.185	0.0746	15.36			1756		138		-0.34	0.015262						
	CL02-577	1	1.072	1.226	0.0774	12.55			1336					0.016967						
		2	1.075	1.231	0.0782	11.83			1231					0.017415						
		3	1.068	1.227	0.0791	13.30	1.14	1.11	1353	116	113	1255		0.017726	0.017373	0.000305667	1.071	0.003092	0.078	0.000709
		4	1.068	1.225	0.0784	10.63			1102				-1.33	0.017384						
	CL02-578	1	1.029	1.177	0.0740	15.36			1785					0.014916						
		2	1.029	1.176	0.0734	15.37			1816					0.014666						
		3	1.031	1.174	0.0722	14.66	2.58	2.52	1792	28	28	1811		0.014175	0.014671	0.000344597	1.030	0.000702	0.073	0.00086
		4	1.029	1.177	0.0740	15.91			1848					0.014926						
	Air	1	0.990	1.132	0.0708	19.4			2463					0.013114						
		2	0.989	1.130	0.0704	19.2			2465					0.01295						
		3	0.991	1.130	0.0696	19.4	0.11	0.11	2555	43	42.00	2495		0.012678	0.012905	0.000177505	0.990	0.000775	0.070	0.000476
		4	0.990	1.130	0.0702	19.3			2496					0.012877						
N0497	CL02-576	1	1.185	1.324	0.0694	12.48			1648					0.014928						
		2	1.180	1.321	0.0705	12.26			1572					0.015328						
		3	1.182	1.323	0.0703	12.22	0.12	0.12	1575	35	34	1598		0.015269	0.015211	0.000186108	1.184	0.003321	0.070	0.000445
		4	1.188	1.329	0.0702	12.38			1598					0.015317						
	CL02-577	1	1.225	1.372	0.0734	11.28			1335					0.017248						
		2	1.225	1.372	0.0735	11.39			1343					0.017311						
		3	1.230	1.366	0.0682	11.01	0.16	0.16	1507	115	113	1392	1.00	0.014905	0.016466	0.001097997	1.225	0.004176	0.072	0.002409
		4	1.219	1.363	0.0718	11.19			1384					0.016403						
	CL02-578	1	1.185	1.323	0.0694	11.80			1559					0.014918						
		2	1.189	1.330	0.0708	12.00			1527					0.015558						
		3	1.173	1.314	0.0705	12.49	0.31	0.30	1601	34	33	1570		0.015247	0.015207	0.000264984	1.180	0.007388	0.070	0.000561
		4	1.175	1.315	0.0701	12.29			1592		28			0.015104						
	Air	1	1.174	1.313	0.0695	12.9			1705					0.014821						
		2	1.169	1.308	0.0698	12.6			1651					0.014877						
		3	1.167	1.307	0.0699	12.5	0.54	0.53	1630	75	73.58	1696		0.014926	0.014885	4.67679E-05	1.171	0.004006	0.070	0.000178
		4	1.175	1.315	0.0697	13.7			1799					0.014916						
N1059	CL02-576	1	1.243	1.386	0.0713	16.59			2078					0.016491						
		2	1.238	1.383	0.0730	17.36			2074					0.017239						
		3	1.242	1.385	0.0714	17.66	2.56	2.51	2206	347	341	1948		0.016527	0.016964	0.000534857	1.243	0.004292	0.072	0.001079
		4	1.248	1.395	0.0735	12.16			1435				-1.48	0.017599						
	CL02-577	1	1.282	1.429	0.0733	9.34			1106				-1.39	0.017993						
		2	1.283	1.423	0.0703	12.79			1649					0.016494						
		3	1.276	1.421	0.0726	12.10	1.52	1.49	1464	227	223	1421		0.017509	0.01733	0.000521499	1.279	0.004061	0.072	0.001266
		4	1.275	1.419	0.0722	11.99			1465					0.017325						
	CL02-578	1	1.232	1.369	0.0688															
		2	1.242	1.382	0.0702	16.84			2179					0.015934			1.240	0.014909	0.071	0.001239
		3	1.241	1.384	0.0715	18.15	1.75	1.71	2260	237	232	2084		0.016567	0.016388	0.000382348				
		4	1.238	1.382	0.0718	14.69			1815					0.016664						
	Air	1	1.176	1.311	0.0677	19.5			2710					0.014062						
		2	1.168	1.303	0.0673	17.4			2444					0.013805						
		3	1.171	1.312	0.0703	14.5	2.05	2.01	1872	374	366.57	2276		0.015156	0.014629	0.000804831	1.171	0.003557	0.069	0.001886
		4	1.168	1.310	0.0712	16.5			2077					0.015492						
V747	CL02-576	1	0.863	1.001	0.0693	13.91			1845					0.011044						
		2	0.874	1.008	0.0669	13.73			1953					0.010397						
		3	0.868	1.008	0.0702	14.51	0.36	0.35	1877	316	310	1854		0.011394	0.011109	0.000517376	0.867	0.005321	0.069	0.001714
		4	0.863	1.005	0.0710	13.77			1742					0.011603						
	CL02-577	1	0.898	1.041	0.0718	9.88			1222					0.012321						
		2	0.893	1.033	0.0700	9.41			1223					0.011643						
		3	0.900	1.041	0.0707	9.66	0.24	0.23	1232	6	6	1226		0.011955	0.011973	0.000384081	0.897	0.003164	0.071	0.000727
		4	0.900	1.041	0.0705															
	CL02-578	1	0.861	1.007	0.0731	15.02			1789					0.012324						
		2	0.854	1.001	0.0736	14.32			1685					0.012393						
		3	0.875	1.011	0.0684	13.76	0.56	0.55	1871	83	81	1798		0.010901	0.01169	0.00076343	0.865	0.009136	0.071	0.002566
		4	0.871	1.010	0.0693	13.93			1848					0.011141						
	Air	1	0.865	1.005	0.0701	15.2			1968					0.011328						
		2	0.866	1.004	0.0692	14.7			1953					0.011052						
		3	0.864	1.004	0.0697	14.4	0.49	0.48	1886	77	75.75	1901		0.011202	0.011242	0.000144988	0.864	0.002365	0.070	0.000497
		4	0.860	1.001	0.0704	14.0			1799					0.011386						
V884	CL02-576	1	0.986	1.124	0.0688	13.21			1778					0.012319						
		2	0.981	1.120	0.0695	13.00			1712					0.012536						
		3	0.992	1.130	0.0693	13.46	0.19	0.18	1784	37	36	1749		0.012579	0.012571	0.00021365	0.988	0.005334	0.069	0.000494
		4	0.993	1.133	0.0700	13.25			1723					0.01285						
	CL02-577	1	1.008	1.151	0.0719	10.28			1266					0.013783						
		2	1.013	1.154	0.0709	9.93			1259					0.013433						
		3	1.015	1.164	0.0743	10.10	0.37	0.36	1164	54	53	1215		0.014856	0.013951	0.000610001	1.013	0.003421	0.072	0.001471
		4	1.015	1.158	0.0716	9.43			1173					0.013733						
	CL02-578	1	0.991	1.125	0.0668	12.82			1833					0.011634						
		2	0.987	1.127	0.0698															
		3	0.988	1.123	0.0675	13.21	0.30	0.29	1848	62.59	61	1805		0.01186	0.012116	0.000734811	0.989	0.001911	0.069	0.001671
		4	0.988	1.128	0.0702	13.40			1733					0.012855						
	Air	1	0.988	1.126	0.0687	14.4			1943					0.012325						
		2	0.989	1.130	0.0704	13.0			1676					0.012944						
		3	0.985	1.124	0.0696	14.3	0.65	0.64	1884	119	116.47	1818		0.012615	0.012693	0.000279043	0.989	0.003021	0.070	0.000704
		4	0.992	1.132	0.0701	13.7			1768					0.012888						

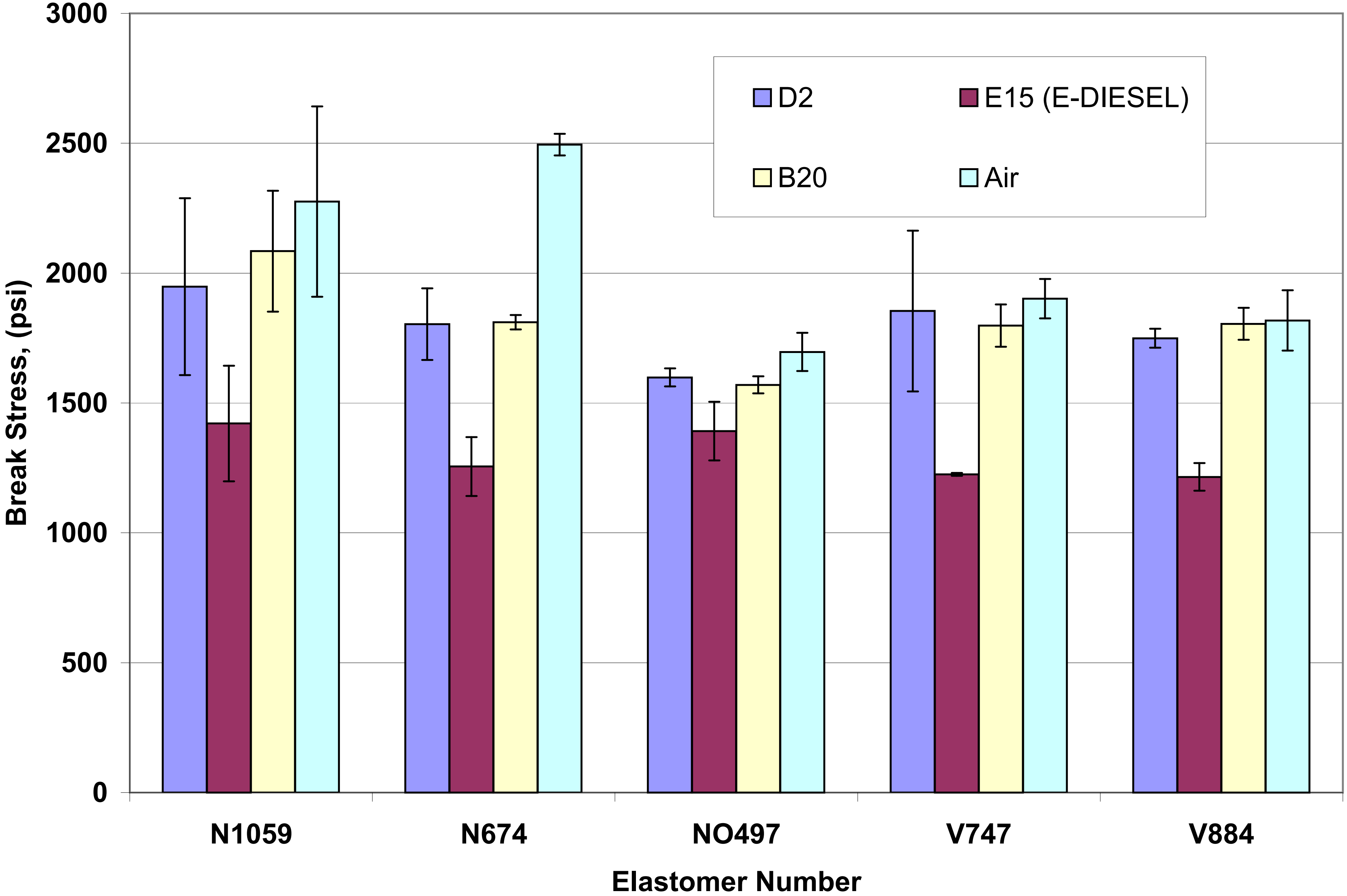
0-ring	Condition	Average Break Load (lbs)	Std. Dev. Break Load (lbs)	95% Conf. Int. Break Load (lbs)	Average Break Stress (psi)	Std. Dev. Break Stress (psi)	95% Conf. Int. Break Stress (psi)
N1059	CL02-576	15.94	2.56	2.51	1948	347	341
	CL02-577	11.56	1.52	1.49	1421	227	223
	CL02-578	16.56	1.75	1.71	2084	237	232
	Air	16.98	2.05	2.01	2276	374	367
N674	CL02-576	15.71	1.26	1.24	1803	140	138
	CL02-577	12.08	1.14	1.11	1255	116	113
	CL02-578	15.33	2.58	2.52	1811	28	28
	Air	19.32	0.11	0.11	2495	43	42
NO497	CL02-576	12.34	0.12	0.12	1598	35	34
	CL02-577	11.22	0.16	0.16	1392	115	113
	CL02-578	12.15	0.31	0.30	1570	34	33
	Air	12.95	0.54	0.53	1696	75	74
V747	CL02-576	13.98	0.36	0.35	1854	316	310
	CL02-577	9.65	0.24	0.23	1226	6	6
	CL02-578	14.26	0.56	0.55	1798	83	81
	Air	14.56	0.49	0.48	1901	77	76
V884	CL02-576	13.23	0.19	0.18	1749	37	36
	CL02-577	9.94	0.37	0.36	1215	54	53
	CL02-578	13.14	0.30	0.29	1805	63	61
	Air	13.8575	0.65	0.64	1818	119	116

0-ring	Exposure	Average Inside Diameter *(in)*	95% Conf. Int. Inside Diameter *(in)*	Average O-ring Thickness *(in)*	95% Conf. Int. O-ring Thickness *(in)*	Average Break Load (lbs)	95% Conf. Int. Break Load (lbs)	Average Break Stress (psi)	95% Conf. Int. Break Stress (psi)	Average Volume *(in^3)*	95% C.I. Volume *(in^3)*
N1059	CL02-576	1.243	0.004292	0.072	0.001079	15.94	2.51	1948.3	340.5	0.016964	0.000535
	CL02-577	1.279	0.004061	0.072	0.001266	11.56	1.49	1421.0	222.6	0.017330	0.000521
	CL02-578	1.240	0.014909	0.071	0.001239	16.56	1.71	2084.4	232.4	0.016388	0.000382
	Air	1.171	0.003557	0.069	0.001886	16.98	2.01	2275.7	366.6	0.014629	0.000805
N674	CL02-576	1.033	0.001661	0.074	0.000164	15.71	1.24	1803.4	137.6	0.015169	0.000078
	CL02-577	1.071	0.003092	0.078	0.000709	12.08	1.11	1255.4	113.3	0.017373	0.000306
	CL02-578	1.030	0.000702	0.073	0.000860	15.33	2.52	1810.6	27.7	0.014671	0.000345
	Air	0.990	0.000775	0.070	0.000476	19.32	0.11	2494.8	42.0	0.012905	0.000178
NO497	CL02-576	1.184	0.003321	0.070	0.000445	12.34	0.12	1598.4	34.4	0.015211	0.000186
	CL02-577	1.225	0.004176	0.072	0.002409	11.22	0.16	1392.0	112.8	0.016466	0.001098
	CL02-578	1.180	0.007388	0.070	0.000561	12.15	0.30	1569.8	33.2	0.015207	0.000265
	Air	1.171	0.004006	0.070	0.000178	12.95	0.53	1696.4	73.6	0.014885	0.000047
V747	CL02-576	0.867	0.005321	0.069	0.001714	13.98	0.35	1854.4	309.6	0.011109	0.000517
	CL02-577	0.897	0.003164	0.071	0.000727	9.65	0.23	1225.5	5.6	0.011973	0.000384
	CL02-578	0.865	0.009136	0.071	0.002566	14.26	0.55	1798.3	81.3	0.011690	0.000763
	Air	0.864	0.002365	0.070	0.000497	14.56	0.48	1901.4	75.8	0.011242	0.000145
V884	CL02-576	0.988	0.005334	0.069	0.000494	13.23	0.18	1749.2	36.4	0.012571	0.000214
	CL02-577	1.013	0.003421	0.072	0.001471	9.94	0.36	1215.2	53.2	0.013951	0.000610
	CL02-578	0.989	0.001911	0.068	0.001671	13.14	0.29	1804.7	61.3	0.012116	0.000735
	Air	0.989	0.003021	0.070	0.000704	13.86	0.64	1817.7	116.5	0.012693	0.000279

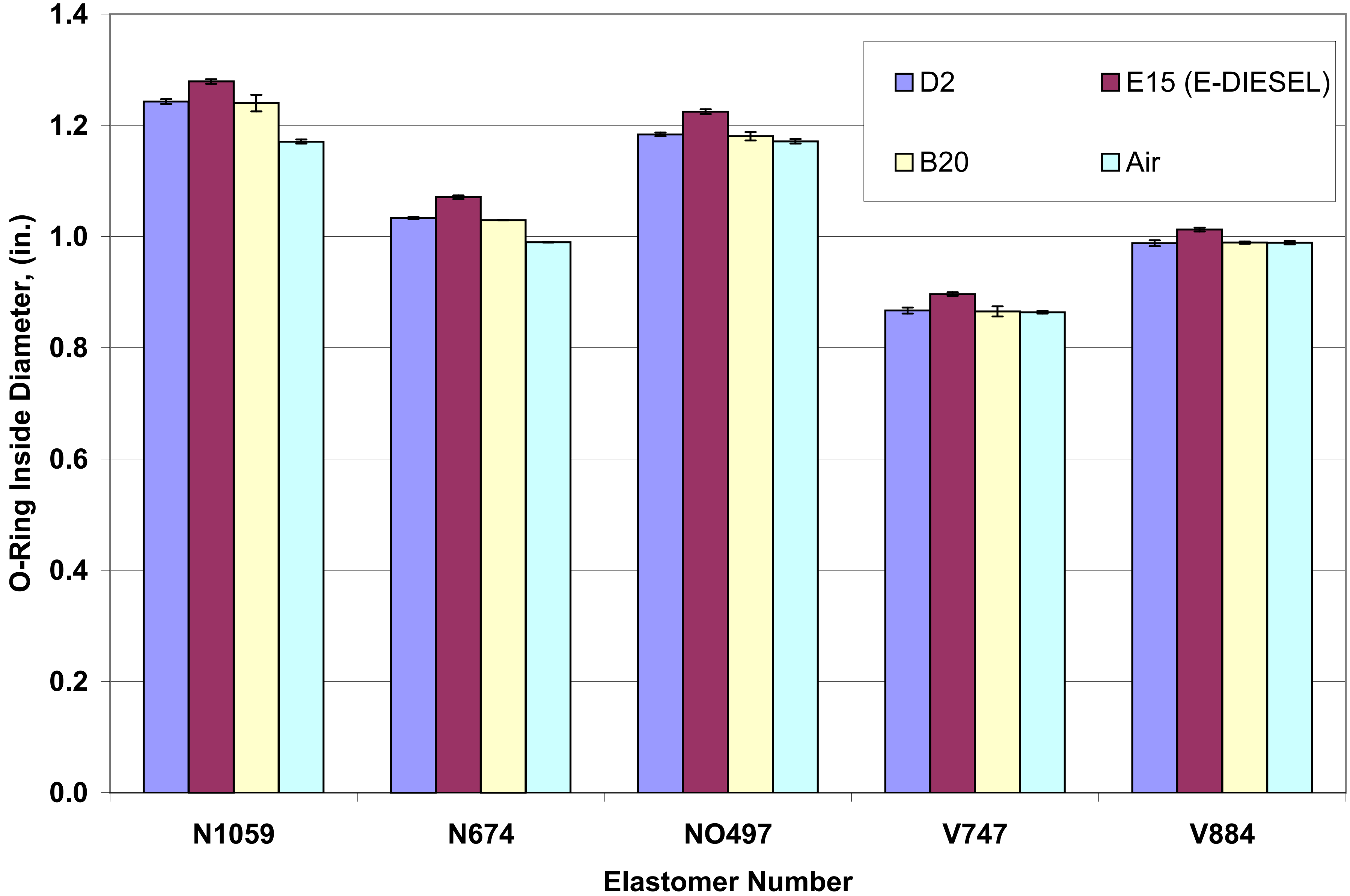
Appendix C:
Bar Graphs with 95% Confidence Bands

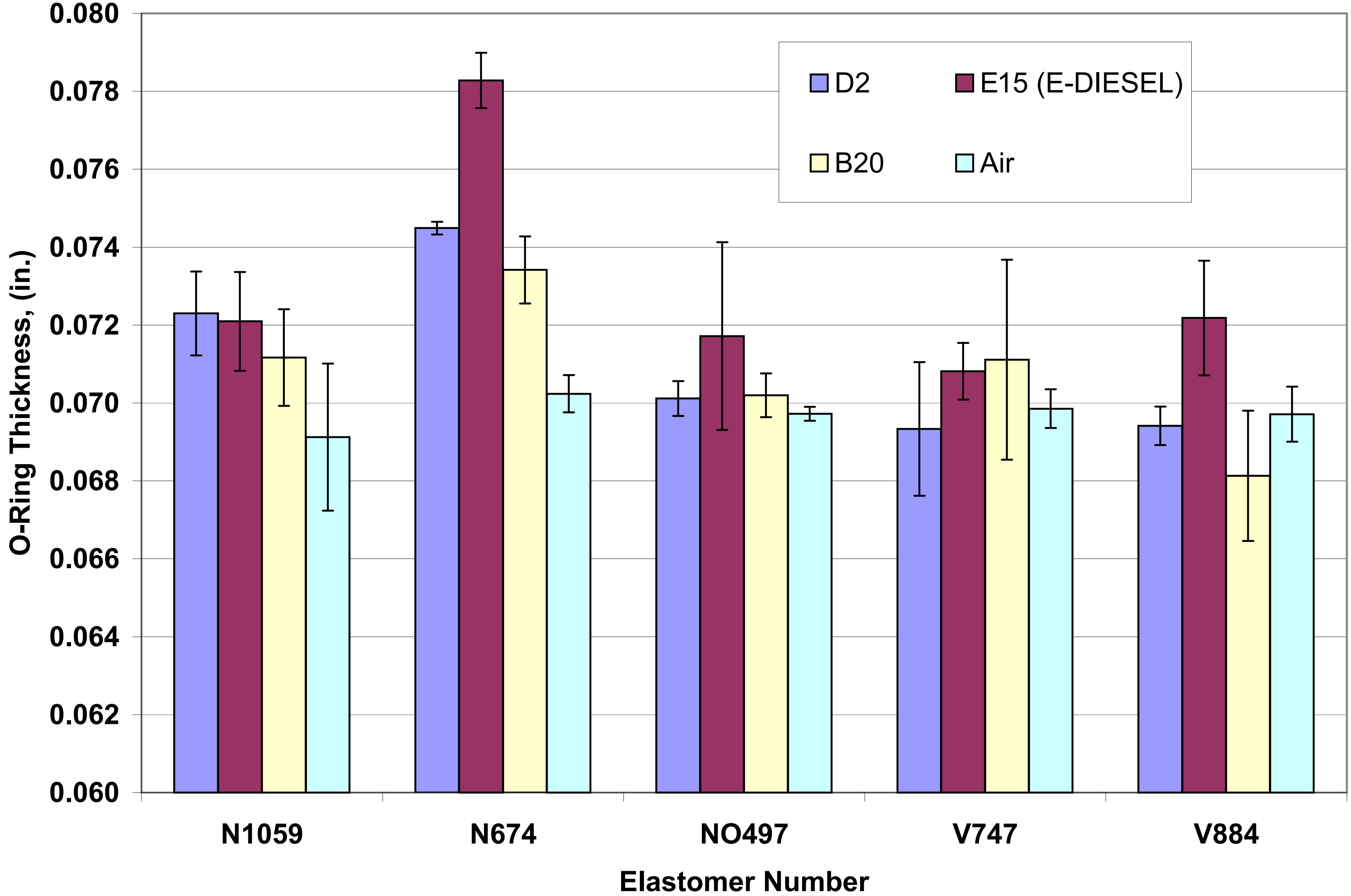


25
20
15
10
5
0
Break Load, (lbs)
D2
E15 (E-DIESEL)
B20
Air
N1059
N674
NO497
V747
V884
Elastomer Number

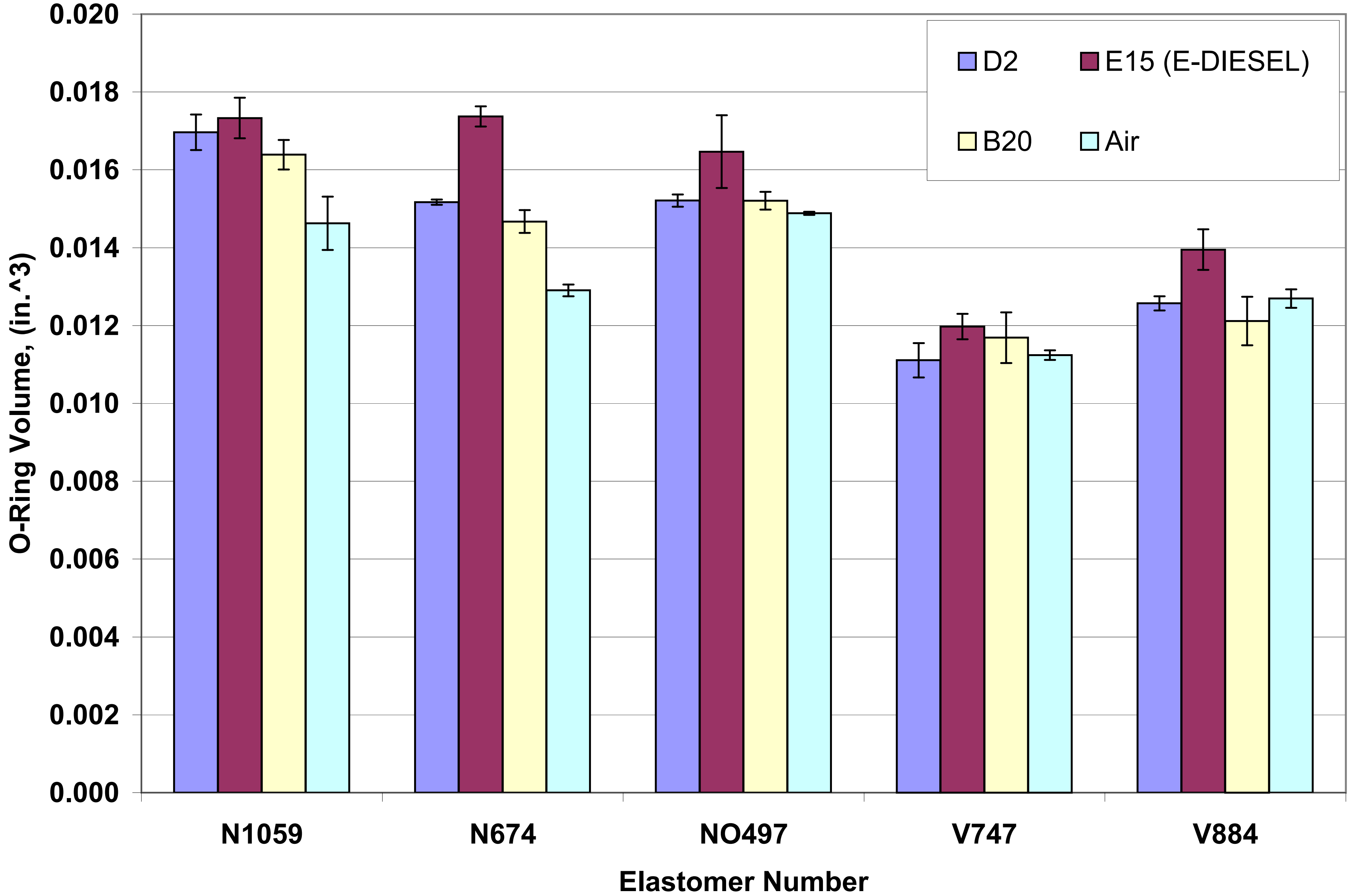


3000
2500
2000
1500
1000
500
0
Break Stress, (psi)
D2
E15 (E-DIESEL)
B20
Air
N1059
N674
NO497
V747
V884
Elastomer Number


1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
O-Ring Inside Diameter, (in.)
D2
E15 (E-DIESEL)
B20
Air
N1059
N674
NO497
V747
V884
Elastomer Number



0.080
0.078
0.076
0.074
0.072
0.070
0.068
0.066
0.064
0.062
0.060
O-Ring Thickness, (in.)
D2
E15 (E-DIESEL)
B20
Air
N1059
N674
NO497
V747
V884
Elastomer Number



0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
O-Ring Volume, (in.^3)
D2
E15 (E-DIESEL)
B20
Air
N1059
N674
NO497
V747
V884
Elastomer Number

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