A Review of the Literature on Soot Production During In Situ Burning of Oil

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Abstract

This paper reviews the available literature on soot, or smoke, production during an in situ burn of oil. The purpose was to determine the range of smoke yields generated by burning petroleum oils on water, and to determine the effects of the size of the fire and the type of fuel which is burned. Forty-eight publications were reviewed. The data from the literature is summarized in tabular form. Graphs were prepared showing the relationship between soot production and fire size (diameter) for various types of fuel oils and crudes. The natural variability of fires and the challenges in measuring soot yields for large, outdoor fires appears to preclude highly accurate, repeatable measurements. That said, it seems that smoke yields from in situ petroleum fires range: from approximately 1 to 10% for fires less than 10 cm in diameter; from 5 to 15% for fires in the 10 to 100 cm diameter range; and, from 10 to 20% for fires greater than 1 m. For the crude oil data sets, a statistical analysis showed that, with a fairly high degree of confidence, smoke yield increases with fire diameter. On the basis of a simple statistical analysis of the limited number of available data sets for identifiable oil types it appears that most show roughly the same correlation of smoke yield with fire diameter. Only an Arabian crude data set appeared to have a significantly different smoke yield vs. fire diameter correlation slope.

An estimate of smoke yield for in situ crude oil fires can be obtained from:

$$\text{Smoke yield (mass\%)} = 4 + 3\,(\log_{10}\,[\text{fire diameter in cm}])$$

The correlation coefficient for this fit is 0.697. Predictive equations with higher correlation coefficients are presented for specific crude oils.

1.0 Introduction

In-situ burning is an attractive response tool for mitigating an oil spill on water. This technique can be relatively quick, it minimizes problems of disposal of collected oil and oily debris, and it takes less equipment than does collection of the oil using booms and skimmers. However, one recognized drawback to *in situ* burning is the smoke which is produced.

This paper reviews the available literature on soot production during *in situ* burning of oil to determine the range of smoke yields generated by *in situ* burning of petroleum oils on water, and to determine the effects of the size of the fire and the type of fuel that is burned.

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2.0 Literature Review

Forty-eight papers were reviewed for this project. The papers are listed in the Reference section and notes on each reference are presented in Table 1.

Graphical summaries that show the relationship between soot production and fire diameter were prepared with the data from the papers. Only those data sets in which soot yields were reported in mass of soot per mass of fuel were plotted. The figures are grouped by fuel type, in pairs, as follows:

- Figures 1 & 2 - Data from all sources
- Figures 3 & 4 - Data from petroleum fuels where fire size information is available
- Figures 5 & 6 - Data from different refined fuels
- Figures 7 & 8 - Data from different crude oils
- Figures 9 & 10 - Data from crude oils of known type
- Figures 11 & 12 - Data from crude oils with a third order polynomial fit

The first graph in each pair (i.e., Figures 1, 3, 5, 7, 9 and 11) shows only the data sets in which all of the soot particles were sampled by the experimental technique. The second graph (i.e., Figures 2, 4, 6, 8, 10 and 12) also includes data sets for which the reported soot yields have been adjusted to take into account measurements (reported values of soot yield) which are known by the investigator to need to be adjusted or, based on the report, are clearly lower than the total amount of soot which is produced by the fire. For example, Einfeld and Morrison (1996) note that the values they report for soot production (0.94-1.96%) are probably only about one-half of the total amount of soot produced. Therefore, their reported values were multiplied by two before recording them in Figures 2, 4, and 6. The methods used to correct these data are discussed in Table 1.

In Figures 3 through 10, least-squares regression fits to the data are shown using a linear equation of the form $y = b + m(\log_{10}x)$. These were used to assess the effects of fire diameter and fuel type on soot yield.

Forty-eight papers were reviewed in preparing this study. There are more papers available that deal with soot produced from hydrocarbon fires, but many of these are not relevant to burning oil on water because the burn conditions were not comparable. For example, several papers were reviewed that deal with smoke produced from the burning oil from well fires in Kuwait in 1991. After reviewing these papers, it became clear that the combustion conditions (and the resulting soot yield) for a well fire are very different from *in situ* burning of oil on water for the following reasons:

1. Water and low molecular weight hydrocarbon materials (methane, ethane, propane, etc.) are produced in a well blowout and are involved in a well fire. The addition of both water and low molecular weight hydrocarbons will result in fires that produce less smoke than a typical oil pool fire, e.g., from crude oil on water.
2. The vigorous turbulent mixing of air with the high velocity effluent from a freely flowing, uncontrolled well blowout will result in much more efficient combustion than will result from the relatively mild mixing condition of *in situ* burning of oil on water, whether the *in situ* burn is

characterized as being in the laminar flow regime or is nominally turbulent.

Because the above understanding was not initially obvious, and because it is instructive to show some citations that are not directly related to *in situ* burning of oil on water, there are some references included in Table 1 that do not involve *in situ* burning. These include references 1, 5, 6, 19, 23, and 24.

2.1 Figures 1 and 2: All Data Sets

Figure 1 shows the data from all the data sets reviewed that measured all soot particle sizes using the experimental technique. The key to the symbols is given on the following pages. The flow regimes, relating to ranges of fire diameters, shown above the abscissa are based on Reynolds numbers estimated by Hottel (1959) for data from Blinov and Khudiahkov (1957). The terms used in calculating the Reynolds number were pan diameter, liquid burning velocity, liquid density and cold fuel vapor viscosity (see Hottel, 1959 for a full derivation). There is considerable scatter in the data (which may be due to the variable nature of fires, including the absence of a vigorous burn phase in some large-scale experiments); however, some general trends are apparent. In the laminar flow regime (diameters up to approximately 10 cm) soot yields vary widely, from about 1% to greater than 10%. In the transition zone (10 to 100 cm diameter) yields range from 5 to 15%. In the turbulent regime (greater than 100 cm diameter) soot yields range from 10 to 20%.

Figure 2 is a variation of Figure 1 in which the data sets that reported soot yields for particle diameter less than 10 microns (PM_{10}) or less than 3.5 microns ($PM_{3.5}$) are shown. Table 2 relates the particle diameter selected to the cumulative mass percentage of the smoke (from McGrattan et al., 1997). These soot yields were adjusted, as noted in Table 1, to reflect sampling all particle sizes. Comparison of Figures 1 and 2 shows that several of the data sets with adjusted soot yields fall below the general trend, particularly the data from Einfeld and Morrison (1996) for JP8 (shown as the symbol B on Figure 2), that of Radke et al. (1990) for JP4 (shown as the symbol ■ on Figure 2) and the data from two 100 m diameter crude oil pool fires in Kuwait (Laursen et al., 1992 - shown as the symbol U).

2.2 Figures 3 and 4: All Oil Types

Figure 3 shows the data used in Figure 1 for which smoke yield is available, for an identifiable oil type, over a range of fire sizes. The least squares correlations are shown in order to determine whether or not fuel type plays a role in smoke yield. The jet fuel data at 5 cm diameter is included because it was used in Figure 4.

A statistical analysis of the data in Figure 3 is given in Tables 3 and 4. Kerosene was not included in the comparison of Table 4 because of the low number of data points. This analysis indicates that smoke yield from Arabian crude is significantly different (higher slope) than that of any other fuel at a 95% confidence limit and that Alberta Sweet Mixed Blend (ASMB) crude is different (higher slope) than Louisiana crude at the same confidence limit. Interestingly, the statistical analysis indicates that there is no significant difference between diesel and any other fuel (except, of course, Arabian crude). Additional discussion of the effects of fire diameter for various groups of fuels follows.

Figure 4 shows the same as Figure 3, with the addition of the adjusted data sets that did not involve collecting all particle sizes. In this case the data for jet fuels appears considerably different from all other fuels. This may be an artifact of the experimental techniques used in obtaining these data points.

2.3 Figures 5 and 6: Refined Fuels

Figure 5 shows the smoke yields (for experiments that measured all particle sizes) for refined fuel burns only. The data are the same as given in Figures 1 and 3 and are plotted only to more clearly show the trends for refined fuels. There appears to be a trend of increasing soot yield with increasing fire diameter for diesel fuel but the correlation coefficient given in Table 3 is low - 0.459 - giving little confidence in the trend. The correlation coefficients for the least squares fits for kerosene in Table 3 is so low - 0.051 - that no correlation between smoke yield and fire diameter is indicated. This is likely due to the low number of data points for kerosene over a small diameter range.

Figure 6 shows the same as Figure 5 with the addition of the extra adjusted data sets. Again, the anomalous trend of the adjusted jet fuel data is apparent.

2.4 Figures 7 and 8: Crude Oils

Figure 7 shows the smoke yields (again from Figures 1 and 3) for identifiable crude oils for which data over a range of fire diameters was available. The ASMB, Alaska North Slope (ANS) and Arabian crude data all have linear regression correlation coefficients (see Table 3) higher than 0.85, indicating a reasonable fit of a straight line to a semi-log plot of the data. The correlation coefficient of 0.645 for the Louisiana crude data is less satisfactory. As noted in Table 3, the slope of the least squares regression for Arabian crude is significantly higher than all the others. The slope of the ASMB crude data is also significantly different from that of the Louisiana crude. All the rest of the data sets are not significantly different. Figure 8 shows the same data, with the inclusion of some extra adjusted data points for ASMB crude from the NOBE burns reported in Ross et al. (1996). Visually, this makes little difference to the linear fit to the data.

2.5 Figures 9 and 10: Crude Oils Fit with First Degree Polynomial

Figure 9 shows a linear regression straight line fit to all the crude oil data for which all smoke particle sizes were sampled. This includes some data not in Figure 7, specifically for Cook Inlet crude and Norman Wells crude, since these were available from only one fire diameter. The least squares correlation coefficient to a semi-log plot of these data is 0.697.

Figure 10 shows the data of Figure 9 plus the adjusted crude oil data (the NOBE results from Ross et al., 1996 and the Kuwait pool fire data from Laursen et al., 1992). The correlation coefficient is reduced to 0.595 by the inclusion of the adjusted smoke yields.

2.6 Figures 11 and 12: Crude Oils Fit with Third Degree Polynomial

The effects of the turbulence regime on crude oil soot production is explored in Figures 11 and 12, which show a third order polynomial fit to the semi-log data for crude oils. There is no physical significance to this sort of fit, but it does illustrate that the data behave in a manner that one would expect.

Soot yields initially decline in the laminar fire zone, i.e., up to about 10 cm diameter (with declining burn rates after Hottel's, 1959, analysis of Blinov and Khudiakov's, 1957, data shown on Figure 13), followed by an increase in soot yield with fire diameter through the transition zone, i.e., from about 10 to 100 cm diameter (with increasing burn rate), followed by a levelling off in the turbulent zone, i.e., above about 100 cm diameter, as air flow into the fire begins to control the soot yield (and burn rate). The apparent decline in smoke yield at very large diameters may represent some other process occurring, such as increased radiation to the fuel surface, the onset of oxygen deprivation in the center of the fire, or the fire splitting into smaller zones that permit better aeration.

On the other hand, the apparent variation of soot yield with fire diameter may simply reflect variability in the data.

3.0 Conclusions

Some of the references give data for soot production from burning of hydrocarbon materials other than crude oils on water. The data in these references indicate:

1. Pool fires from aromatic hydrocarbons such as toluene appear to produce much more soot than similar fires with crude oil.
2. Pool fires of lower molecular weight non-aromatic hydrocarbons (hexane, heptane, nonane, etc.) produce an order of magnitude less soot than crude oil fires.
3. Burning asphalt shingle fires produce about the same amount of soot as crude oil fires.

It is difficult to draw all but very general conclusions from the data. The natural variability of fires and the challenges in measuring soot yields for large, outdoor fires, appears to preclude highly accurate, repeatable measurements. That said, it appears that smoke yields from *in situ* petroleum fires range from approximately: 1 to 10% for fires less than 10 cm in diameter; 5 to 15% for fires in the 10 to 100 cm diameter range and from 10 to 20% for fires greater than 1 m. For the crude oils, the statistical analysis shows that, with a fairly high degree of confidence, smoke yield increases with fire diameter. On the basis of a simple statistical analysis of the data sets for identifiable oil types it appears that only Arab crude has a significantly different smoke yield vs. fire diameter correlation than the other fuels, which generally do not have significantly different correlation slopes from each other.

A rough estimate of smoke yield for *in situ* crude oil fires can be obtained from:

$$\text{Smoke yield (mass\%)} = 4 + 3\ (\log_{10}\ [\text{fire diameter in cm}])$$

The correlation coefficient for this fit is 0.697. Predictive equations with higher correlation coefficients could be developed for specific crude oils.

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Table 1 - NOTES ON THE LITERATURE OF SOOT PRODUCTION DURING IN SITU BURNING OF OIL

Source (Reference)		Fuel	Fire Size	Smoke Measurement	% Soot Rep.	% Soot Adj.	Comments/Notes
1	Bauer	Crude oil Kuwait fires	1.5 to 7 MMB/D	Author took two estimates provided by others	5 (est.)		Burning wells--Kuwait. Geometry and air/fuel mixing energy was much different from an oil pool on water.
3	Day & Mackay	Crude oil	8.9 cm 13.0 g 12.0 g 12.1 g 12.5 g 13.2 g 12.4 g 16.6 g 8.3 g	Collected all soot on filters, weighed	 1.2 4.3 2.9 2.8 1.8 2.7 2.1 4.5		Varied air flow in some experiments; this was an important parameter in determining the test results. Also looked at the original fuel temperature (not a very important parameter) and the original thickness of the oil (which appeared to have an inverse effect on soot production in these experiments). Also, please note that the test conditions involved burning oil contained in a brass dish (to which were attached tubing through which a fluid could be circulated to control the temperature of the oil pool) resting on a sand bed. Thus, the test apparatus and conditions did not truly reflect in situ burning of oil on water. These data are shown in Figures 1 and 2 using symbol "A". These data have not been included in other Figures because the crude oil used in these tests was not identified by the authors.

2 4	Brown, Dod, *et al.* and Dod, Brown, *et al.*	Asphalt shingles	1.9 m x 1.2 m	Collected soot sample (isokinetic sampling) on filter and weighed; compared with measured fuel weight loss during period of sampling--two tests.	13.94 10.22		The first paper (Brown, Dod, et al--Reference 2) describes the experimental conditions. These tests were conducted to investigate the contribution to "nuclear winter" of the burning of asphalt shingles, among other substances. Thus, these experiments are not directly comparable with in situ burning of oil on water, but the relative amounts of smoke are believed to be similar. These data are not included in the attached figures because the test conditions are not reflective of oil burning on water.
5	Einfeld & Morrison	JP-8	0.5 m 2 kg	Carbon balance	0.94 to 1.96	1.8 to 3.9	Three tests conducted in a sealed chamber. Measured PM_{10}, but noted that total particles (by visual estimation from graph of mass vs particle diam.) were probably $2xPM_{10}$. It is possible that the high volume sampling device used in these experiments did not permit all of the soot particles to travel through the apparatus to be trapped on the appropriate filters. A more likely explanation for the relatively low soot values is that the smoke was all contained inside the test chamber and could recirculate through the combustion zone, which could consume some of the soot. Note that for these experiments the soot sampling did not begin until after the fire had extinguished. Also note that the data from Fleischmann et al. (1990) - reference 23 - show significantly lower soot yields from burns in an enclosed room compared to individual fires in the open. These data are shown in Figure 2 using symbol "B" and in Figures 4 and 6 using symbol"J". In these figures, the data have been adjusted as recommended in the paper (i.e. the numbers have been multiplied by two to include all soot particles).
6	El-Shobokshy & El-Saedi	Crude oil Natural gas	Kuwait fires	No measurements--see comments	0.9		No measurements. Percentage of soot estimated from an EPA report of air emission factors.

7	Evans et al. (1986)	Prudhoe Bay Crude	40 cm 40 cm 60 cm 60 cm	Carbon balance	9.8 7.9 8.0 9.0		These are the first reported results of a series of experiments covering a wide range of experimental variables--see the references by Evans et al. which follow plus the references by McGrattan et al. and Walton et al, below. These data are shown in Figures 1 and 2 using symbol "D" and in Figures 3, 4, 7, 8, 9, 10, 11, and 12 using symbol "P".
8	Evans et al. (1988a)	Alberta Sweet Crude	0.6 m 9 liters	Carbon balance	9.0 9.5 8.0 7.9		Sampling system used has some effect on results obtained, but Evans et al. felt that this had a relatively minor influence on their results. In the first two tests reported, two consecutive measurements were made, indicating that the rate of soot production increased during the test. These data are shown in Figures 1 and 2 using symbol "E" and in Figures 3, 4, 7, 8, 9, 10, 11, and 12 using symbol "A".
9	Evans et al. (1988b)	Alberta Sweet Crude	0.6 m Oil depth: 2 mm 3 mm 5 mm 10 mm 30 mm	Carbon balance	3.5 5.0 8.0 8.0 10.0		This series of experiments was conducted primarily to investigate the effect of oil pool thickness on smoke emission from in situ burning. The smaller thicknesses and smaller smoke yields correspond to transient burning phases, in which smoke yield is reduced as the result of boiling of the underlying water layer. The 30 mm oil thickness experiment and 10 % smoke yield correspond more nearly to steady burning. The data for 30 mm oil thickness are shown in Figures 1 and 2 using symbol "F" and in Figures 3, 4, 7, 8, 9, 10, 11, and 12 using symbol "A".

10	Evans (1988)						This is a review paper. Two burning regimes are observed during burning of oil on water: 1. A initial phase, while the oil layer is relatively thick and the underlying water has not been heated to boiling, and 2. A subsequent, vigorous burning phase, when the oil layer has been reduced sufficiently that the underlying water is heated to boiling. In the vigorous burning phase, the boiling water churns the oil layer, throwing water and oil droplets into the flame; and the energy release rate increases by a factor of two to four times the pre-boiling rate. When water is injected into the hydrocarbon flame, the smoke emission rate per unit fuel mass can decrease substantially (as much as a factor of five). [It may be noted that a vigorous burning phase was not observed during the Newfoundland Offshore Burn Experiment (NOBE), presumably because the continual movement of the oil across the water, propelled by the fire-resistant boom, precluded sufficient heating of the underlying water.]
11	Evans et al. (1989a)						No data are presented on soot production in terms of percentage of fuel burned. This paper deals specifically with the effects of soot particle agglomeration on settling of soot.
12	Evans et al. (1989b)						No new data; the data reported in this paper are from Evans et al. (1988a).
13	Evans *et al.* (1990)						This paper does not contain any data on soot production. It describes test procedures, measurement techniques used in laboratory and field tests, and describes methods for predicting the trajectory of the smoke plume which results from in situ burning. It is a good review paper.

14 15	Evans et al. (1991a and 1991b)	Diesel " " Arab. Lt. and Murban crude mix " ANS ASMB	40 cm 1.5 m 1.0 m 3 m 40 cm 60 cm 60 cm	Carbon balance	13.0 14.2 20 8.0 9.5 10.2 11.0 13.5 14.5 15.5 7.8 9.7 8.5 9.0 7.0 11.0		This paper describes the instrumentation used to sample the soot produced from relatively large fires (e.g., 1 m diameter and larger) as well as the instrumentation used for smaller, laboratory-scale fires (e.g., 40 cm diameter). The paper notes that the burning rate per unit area increases strongly with the size of the experiment, reflecting a change from convection dominated heating of the fuel for small areas (e.g., 0.1 m diameter) to radiative dominated heating for large fires (e.g., 10 m diameter). These data are shown in Figures 1 and 2 using symbol "G" for Arab light + Murban crude mix, symbol "H" for diesel, and symbol "I" for Louisiana crude. The data for crude oils are shown in Figures 3, 4, 7, 8, 9, 10, 11 and 12 using symbol "R" for Arabian crude and symbol "L" for Louisiana crude. The data for diesel oil are shown in Figures 3, 4, 5, and 6 using symbol "D".
16	Evans et al. (1992)	Arab. Lt. and Murban crude mix Louisiana Crude Murban Crude Louisiana Crude	8.5 cm 60 cm 2 m 6.88 m 12 m 17.2 m	Carbon balance (also used isokinetic sampling for mass flux, and light extinction for the 8.5 cm, 60 cm and 2 m tests, to study the degree of reliability of the carbon balance method)	5.3 5.2 5.7 5.4 6.3 5.8 6.3 8.0 7.7 8.2 13.9 13.7 7.9 13.7 10.3 12.1 12.7		The values shown are for the carbon balance method, but the results using the other two methods of measuring soot production are essentially identical to these, especially for the smaller diameter fires (maximum variation ±0.7%). These tests are important in validating the reliability of the carbon balance method of measuring soot production. Except as noted below, these data are shown in Figures 1 and 2 using symbol "J" for Arab light + Murban crude mix and symbol "K" for Louisiana crude. The data are shown in Figures 3, 4, 7, 8, 9, 10, 11 and 12 using symbol "R" for Arabian crude and symbol "L" for Louisiana crude. For the largest diameter tests, using Louisiana crude oil, several variations in test procedure were used. In these tests, an external water spray did not significantly reduce smoke emissions and aging the oil prior to ignition did not increase emissions. The data from the test using an external water spray are not included in the Figures.

17	Evans et al. (1993)	Murban and Louisiana					This is essentially a review paper. The data shown in this paper are reported in other papers, e.g., reference 16.
18	Evans (1994)	Louisiana Cook Inlet ANS and ASMB Crudes	1.2 to 17.2m	Carbon balance	9.2 to 15.2		This is a review paper; the data for soot production shown in this paper are also reported in other papers. The values for soot production are consistent with measurements by others of soot production from hydrocarbon fires when the fuel contains relatively high molecular weight species and especially when the fuel contains some aromatic hydrocarbons.
19	Fendell & Mitchell	Crude oil Natural gas	Kuwait fires	No measurements--see comments	1.6 & 2.8		Paper by Fendell & Mitchell is devoted to modelling; they incidentally quote values of smoke emissions, which they obtained from the paper by Hobbs & Radke (see Reference 26, below).
20	Ferek et al. (1992)	Crude oil	NOBE	Carbon balance	8 . 7 avg.		See Reference 43.
21	Ferek et al. (1995)	Crude oil	NOBE	Carbon balance	8 . 7 avg.		See Reference 43.
22	Fingas et al. (1996)						This is a review paper. Fingas et al. believe that use of the carbon balance method gives values of soot production which are too high.
23	Fleischman *et al.*	No. 2 fuel oil	0.56 m 0.56 m 2 pans, each 0.56 m 0.56 m (in room)	Collected soot sample (isokinetic sampling) on filter and weighed; compared with measured fuel weight loss during period of sampling.	11.65 10.95 8.42 7.61 5.06		The decreased soot production with two pans and with the "one pan in room" (the last datum shown) appears to be the result of increased radiation from the flame back to the fuel and more complete combustion. The data for single pans are shown in Figures 1 and 2 using symbol "C" and in Figures 3, 4, 5, and 6 using symbol"D" for No. 2 fuel oil.

24	Hobbs & Radke	Crude oil Natural gas	Kuwait fires		0.3		Article refers to another article in J. Geophysical Res. (in press). Notes that low ratio CO/CO_2 indicates efficient combustion. Some of the fires were from natural gás, which would be expected to produce little soot.
25	Khordagui & Al-Ajmi	Crude oil Natural gas	Kuwait fires	No measurements--see comments	7.3 avg (2.0 - 9.8)		Estimate, based on paper by Ransohoff (not included in this review).
26	Koseki *et al.*	Arab. Lt.	0.6 m	Carbon balance	6		The values for soot, which appear at first to be relatively high, are consistent with measurements by others of soot production from hydrocarbon fires when the fuel contains relatively high molecular weight species and especially when the fuel contains some aromatic hydrocarbons. The data for Arabian light crude oil are shown in Figures 1 and 2 using symbol "S" and in Figures 3, 4, 7, 8, 9, 10, 11, and 12 using symbol "R" for Arab light crude oil.
					7		
			1 m		8		
					10		
			2 m		13		
					16		
			2.7 m □		19		
			0.6 m		10		
		Toluene	1 m		11		
			2 m		35		
			2.7 m □		25		
			0.6 m		0.6		
		Heptane	2 m		1.2		
27	Laursen et al. (1992)	Crude oil Kuwait pool fires	100 m Minagish Magwa	Carbon balance	 4.3 5.2	 6.6 8	Values shown are for particles $<3.5\mu$ diameter. The authors postulate that the relatively low values they found for soot emission may have resulted from relatively efficient combustion, owing to the relatively high temperatures in these pool fires. [NOTE: Based on the relatively small particle sizes measured, it is assumed that the total amount of soot in these fires was actually somewhat greater than reported in the paper. From other work by these authors (see Ref. 42 and 43), we have estimated that the total amount of soot was on the order of 1/0.65 times the values reported. The adjusted data are shown in Figure 2 using symbol "U" and in Figures 10 and 12 using symbol "M".

28	McGrattan *et al.* (1993)	Louisiana ANS Cook Inlet Crudes	1.2 m	Carbon balance	10.1 10.2 11.9 11.4 11.5 8.8 9.3 9.3 9.5		One of the objectives of this study was to explore the effect of fire size on the burning rate and smoke yield. The authors conclude that burning rate increases with the effective diameter of the fire. Based on the limited data in this study plus those from a previous study (see reference 44, below) the authors conclude that there is no effect of fire size on smoke yield for effective fire diameters above about 6.9 m. These data are shown in Figures 1 and 2 using symbol "L" for Louisiana crude, symbol "M" for ANS crude (North Slope crude), and symbol "N" for Cook Inlet crude. The data are shown in Figures 3, 4, 7, 8, 9, 10, 11 and 12 using symbol "L" for Louisiana crude, symbol "P" for ANS crude (North Slope crude), and symbol "C" for Cook Inlet crude.
29	McGrattan et al. (1995)	ANS crude oil	9 m	Carbon balance using RAM (<u>R</u>eal time <u>A</u>erosol <u>M</u>onitor) and non-dispersive infrared CO_2	10		Estimated value only, the dry Arctic air precluded accurate weighing of the filters used to collect soot samples.
30	Mitchell (undated)	Crude oil	2.5 cm 15 ml	Soot collected on fibreglass filter	Soot not report'd		Small amount of soot was lost owing to leakage. Had measurement problems caused by the small mass of soot - resorted to measuring volume of soot instead which, in context, was reasonable because the objective of these tests was to compare relative soot production with and without the use of additives to the fuel .
31	Mitchell (1990)	Crude oils: ASMB Prudhoe Bay	4 cm 16 g 16.5 g	Collected soot on glass fiber filters	 3.8 5.1		Measured volumes of soot and derived soot weights using a measured density of 0.35 g/ml. The derived values are shown in Figures 1 and 2 using symbol "Z" for ASM crude and symbol "●" for Prudhoe Bay crude. In Figures 3, 4, 7, 8, 9, 10, 11 and 12 symbol "A" is used for ASM crude and symbol "P" for Prudhoe Bay crude.

32	Mitchell (1991a)			No measurements			Reports literature survey.
33	Mitchell (1991b)	ASMB Prudhoe Bay Norman Wells	4 cm 15 g	Collected soot on glass fiber filters	1.2 ml 1.6 ml 2.8 ml		Measured volumes of soot. [If compacted soot had density of 0.35 g/ml and all of oil sample burned, mass percentage of soot would range from 2.8 to 6.5%].
34	Mitchell & Moir (1992)	Crude oil Jet A1 Kerosene Varsol Gasoline	Crucible Diam. not reported 10 ml	Collected soot on glass fiber filters	0.08 ml/g 0.11 ml/g 0.13 ml/g 0.16 ml/g 0.24 ml/g		Using same assumptions listed in comments on reference 33, the percentage of soot would range from 2.8 to 8.4%. Differences in soot yield from different fuels, at this scale, were noted.
35	Mitchell (1992b)	Crude oil	3.5 cm	No measurements			The figures in the copy available are not legible.
36	Mitchell (1993)	Crude oil JP4 JP5 JP8	0.9 m 10 kg	Slip streams from the main exhaust duct were passed through PTFE or glass fiber filters			Only reported relative results, not actual numbers.
37	Mitchell (1994)						Notes that National Institute of Standards and Technology (NIST) has reported soot production on the order of 10%. This figure is assumed for JP4.

38	Moir *et al.* (1993)	Crude oil Kerosene Jet A & B Toluene Isooctane Cyclo-hexane Nonane	47 mm	Soot collected on filter and weighed	8.6 11.4 11.4 10.3 16 7.0 4.5 1.5		These data are shown in Figures 1 and 2 using symbol "V" for crude oil (Norman Wells), symbol "W" for Jet A, symbol "X" for Jet B, and symbol "Y" for kerosene. The data are shown in Figures 3, 4, 5, and 6 using symbol "J" for jet fuel and symbol "K" for kerosene.
39	Mullholland et al. (1988)	Prudhoe Bay crude oil Heptane	85 mm 0.4 m 0.6 m 60 mm 85 mm 310 mm 500 mm	Isokinetic sampling to determine mass flux	8.3 8.4 9.6 9.8 9.0 8.5 1.3 1.3 1.5 1.6 0.6 1.0 1.0 1.3 0.9 1.2		Note that burning heptane produced much less smoke than burning crude oil. These data are shown in Figures 1 and 2 using symbol "◆" for ANS (Prudhoe Bay) crude oil. The data for ANS crude are shown in Figures 3, 4, 7, 8, 9, 10, 11, and 12 using symbol "P". Only the data for the 85mm diameter pan experiments are shown because the other data are duplicative of another reference.
40	Patterson et al. (1991)	Kerosene No. 2 diesel No. 5 diesel Asphalt shingles	6x10 cm	Direct capture of soot on filter	2.9 3.3 5.3 9.2		Primarily concerned with light absorption in context of "nuclear winter" studies. Largest amounts of soot were from burning asphalt. These data are shown in Figures 1 and 2 using symbol "□" for kerosene, symbol "▽" for No. 2 diesel, symbol "△" for No. 5 diesel, and symbol "◇" for asphalt and in Figures 3, 4, 5, and 6 using symbol "D" for diesel and symbol "K" for kerosene; asphalt is not shown in Figures 3, 4, 5, and 6.

41	Penner et al. (1986)	Crude oil		No measurements--see comments	3		Primary use of information was to provide input to a smoke plume model. No justification was offered for the assumed value of soot production.
42	Radke et al. (1990)	JP4	30 m	Carbon balance	2.3	3.5	Only sampled particles <3.5 μm diameter. As suggested by Ross et al. (1996) [see Ref. 43] the data reported by the author should probably be adjusted by multiplying by 1/0.65 to account for the total amount of soot produced. The adjusted data are shown in Figure 2 using symbol "■" and in Figure 4 using symbol "J". Also, these samples were collected only from the top layer of the smoke plume at the planetary boundary layer and may not be representative of the entire cross-section of the plume.
43	Ross *et al.* (1996)	Crude oil	Nfld. burn test (NOBE)	Carbon balance	8.7 avg.	13.4	Aerial samples taken during the Newfoundland Offshore Burn Experiment (NOBE). Four samples taken during the first burn, three during the second. Only sampled particles <3.5 μm diameter. [NOTE: Based on paper 5 cited above, this may be <½ of total particulates.] These data are shown in Figure 2 using symbol "P" and in Figures 4,, 8, 10, and 12 using symbol "A". Ross et al. suggest that their data agree with Walton et al. (1994b) [see Ref. 46] if divided by 0.65 to adjust for different smoke particle diameters sampled. The adjusted data are shown in the figures.

44	Walton et al. (1993)	Louisiana crude oil	1 - 1.2m 1 - 6 m (square) 5 - 15m (square)	Carbon balance	10.9 14.6 9.5 10.2 10.3 11.1 11.8		The paper also includes data from previous tests by NIST which indicate that emissions increase with fire diameter. Visual interpolation of graphical data in the paper indicates: Diam., m — % Soot 0.1 — 6 1 — 8 10 — 10 These data are shown in Figures 1 and 2 using symbol "O" and in Figures 3, 4, 7, 8, 9, 10, 11, and 12 using symbol "L".
45	Walton et al. (1994a)	Diesel fuel	6.9 17.2 17.2	Carbon balance	13.6 avg. 13.0 9.5 avg.		These data are shown in Figures 1 and 2 using symbol "R" and in Figures 3, 4, 5, and 6 using symbol "D".
46	Walton et al. (1994b)	ASMB Crude	NOBE 1 13.5 m NOBE 2 11.1 m (est.)	Carbon balance	15.4 avg. 14.9 avg		These data are shown in Figures 1 and 2 using symbol "Q" and in Figures 3, 4, 7, 8, 9, 10, 11, and 12 using symbol "A".
47	Walton et al. (1995)	Diesel	4.7m 8.6m 8.6m	Carbon balance	10.8 15.4 15.1		Data collected during tests of forced aeration to reduce smoke. Only data sets collected without additional air are shown. These data are shown in Figures 1 and 2 using symbol "T" and in Figures 3, 4, 5, and 6 using symbol "D".

48	Wighus (1991)	Fuel oils: SBP 140/165 (similar to kerosene) SBP 62/82 (primarily hexane)	$0.15\ m^2$ $0.3\ m^2$ $0.3\ m^2$	Light extinction	8.5 9.0 2 to 6 1 to 7		The experiments described in this paper were conducted to explore production of soot and toxic gases in a fire on an oil production platform, in closed spaces. They are therefore not directly related to burning of oil on water, but the results are judged to be reasonably comparable. In some of these experiments, an objective was to examine the effects of the fuel/air ratio; soot production was highest when the ratio was close to stoichiometric and decreased as the air/fuel ratio increased. Soot production also increased with increased turbulence in the combustion room. These data are shown in Figures 1 and 2 using symbol "▲" for SBP 140/165 and in Figures 3, 4, 5, and 6 using symbol "K". The data for SBP 62/82 are not shown in the figures because they are essentially for a single component, not a typical fuel or crude oil.

Table 2: Approximate Soot Mass Fraction as a Function of Particle Size

Particle Aerodynamic Size (μm)	Cumulative Mass (%)
All	100
PM-10*	87
PM-5	67
PM-3.5	58
PM-2.5	82
PM-1.0	50

* PM-10 means that this size range includes all Particulate Matter less than 10 μm in diameter

Table 3 - Statistical Data for Least Squares Regression Slope Comparisons for Smoke Yield Data Sets

(Data sets that measured all soot particle sizes only)

Fuel	Slope*	Intercept*	r*	S_x	S_y	$S^2_{y/x}$	n
Diesel	2.236	6.858	0.459	0.779	3.796	12.249	14
Kerosene	0.337	7.548	0.051	0.545	3.629	19.70	4
ANS crude	3.680	3.198	0.778	0.515	2.439	2.64	10
ASMB crude	4.783	0.358	0.942	0.645	3.277	1.330	12
Arab crude	6.659	-2.383	0.865	0.520	4.001	4.222	23
Louisiana crude	2.017	5.513	0.645	0.817	2.552	4.014	20

* smoke yield (mass %) = Intercept + Slope x (Log_{10}[Fire Diameter in cm.])

Table 4 - Statistical Comparison of Regression Slopes for Soot Yield from Various Petroleum Fuels

(Data sets that measured all soot particle sizes only)

Fuels Compared*	$S'^2_{y/x}$	S^2_{b1-b2}	$\|t\|$	$t_{\alpha/2,n1+n2-4}$	significant difference at 95% confidence interval?
Diesel - ANS	8.405	2.878	0.85	2.086	no
Diesel - ASMB	7.286	1.95	1.82	2.074	no
Diesel - Arab	7.141	1.53	3.50	2.042	yes (Arab > Diesel)
Diesel - Louisiana	7.308	1.397	0.18	2.042	no
ANS - ASMB	1.91	0.68	1.34	2.101	no
ANS - Arab	3.786	1.148	2.54	2.042	yes (Arab > ANS)
ANS - Louisiana	3.591	1.0061	1.669	2.056	no
ASMB - Arab	3.289	0.751	2.90	2.042	yes (Arab > ASMB)
ASMB - Louisiana	3.055	0.627	3.493	2.048	yes (ASMB > Louisiana)
Arab - Louisiana	4.126	0.626	5.86	2.021	yes (Arab > Louisiana)

* null hypothesis - there is no difference in the slopes of the least squares regression lines

KEY TO SMOKE YIELD GRAPH

SYMBOL	REF. NO.	REFERENCE AND OIL TYPE
A	3	Day *et al.* (1979) - crude oil not specified
B	5	Einfeld and Morrison (1996) - JP8 corrected
C	23	Fleischmann *et al.* (1990) - No. 2 fuel oil
D	7	Evans *et al.* (1986) - ANS crude
E	8	Evans *et al.* (1987) - ASMB crude
F	9	Evans *et al.* (1988) - ASMB crude
G	17	Evans *et al.* (1991) - Arab/Murban mixed crude
H	17	Evans *et al.* (1991) - Diesel
I	17	Evans *et al.* (1991) - Louisiana crude
J	18	Evans *et al.* (1992) - Murban crude
K	18	Evans *et al.* (1992) - Louisiana crude (excl. water test)
L	28	McGrattan et al. (1993) - Louisiana crude
M	28	McGrattan et al. (1993) - ANS crude
N	28	McGrattan et al. (1993) - Cook Inlet crude
O	44	Walton et al. (1993) - Louisiana crude
P	43	Ross et al. (1996) - NOBE corrected
Q	45	Walton et al. (1994a) - NOBE
R	46	Walton et al. (1994b) - Diesel
S	26	Koseki et al. (1991) - Arabian light crude
T	47	Walton et al. (1995) - Diesel
U	27	Laursen et al. (1992) - Kuwait oil pool fires (corrected)
V	38	Moir et al. (1993) - NW crude
W	38	Moir et al. (1993) - Jet A
X	38	Moir et al. (1993) - Jet B
Y	38	Moir et al. (1993) - Kerosene
Z	31	Mitchell (1990) - ASMB crude
●	31	Mitchell (1990) - ANS crude

◆	39	Mullholland et al. (1988) - ANS crude
□	40	Patterson et al. (1991) - Kerosene
▽	40	Patterson et al. (1991) - No. 2 Diesel
△	40	Patterson et al. (1990) - No. 5 Diesel
◇	40	Patterson et al. (1991) - asphalt
▲	48	Wighus (1991) - SBP 140/165 (like kerosene)
■	42	Radke et al. (1990) - JP4 (corrected)

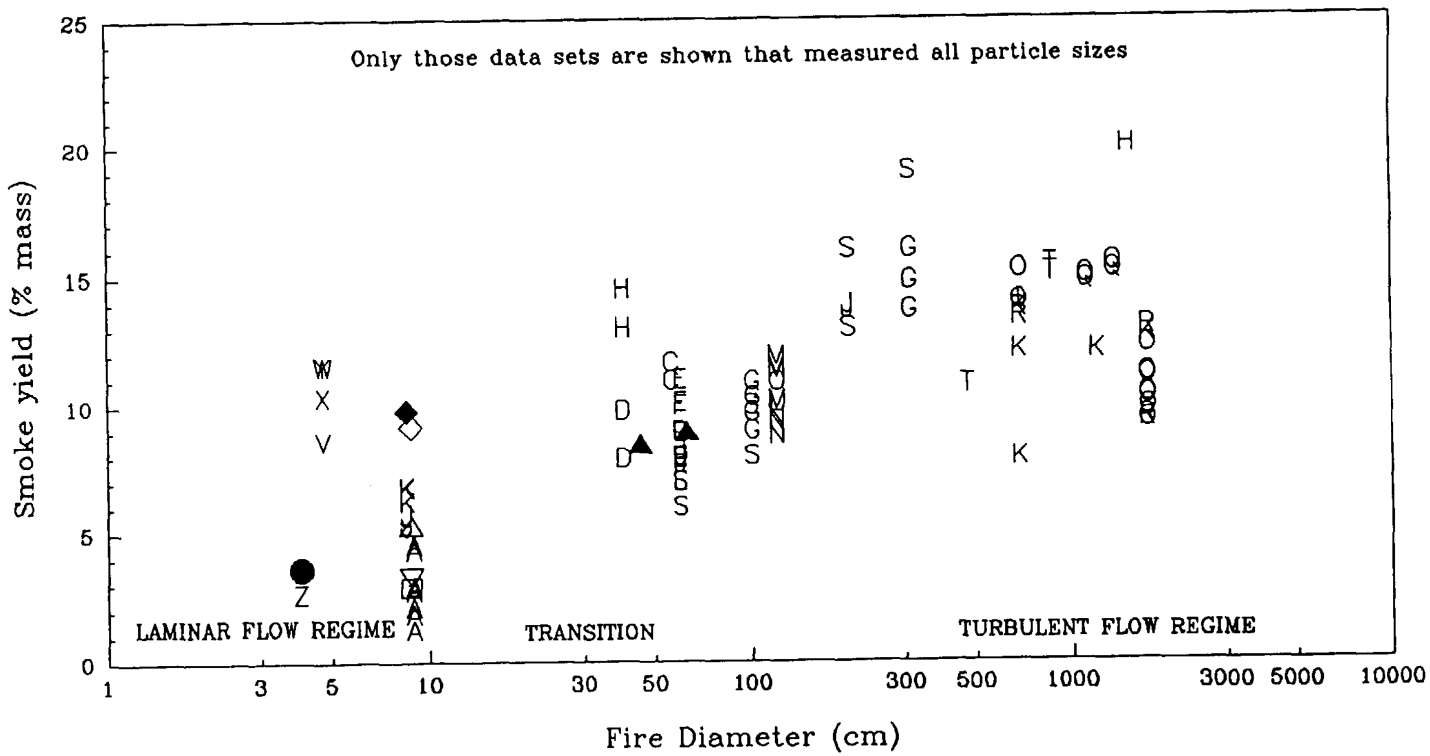

Figure 1: Smoke Yield vs. Fire Diameter – A Comparison of Data Sets

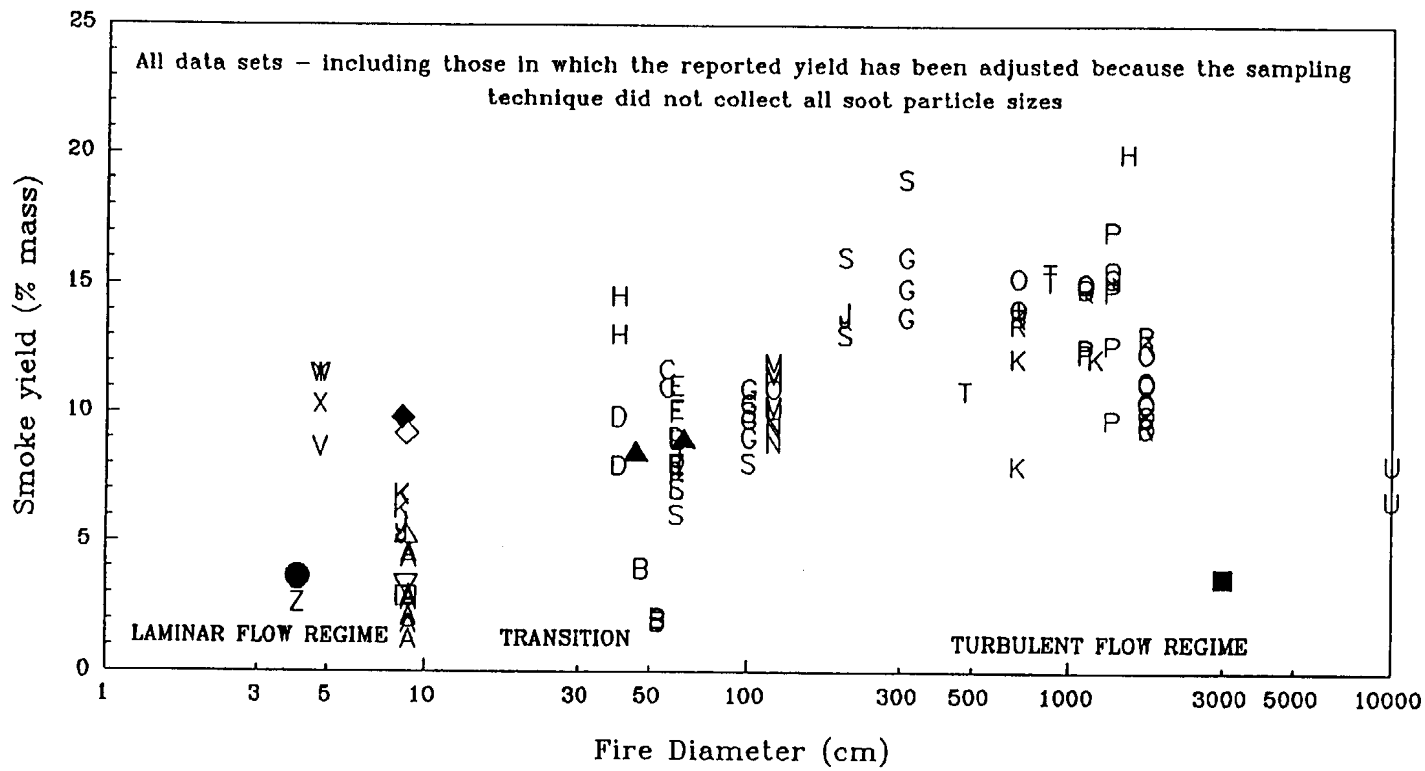

Figure 2: Smoke Yield vs. Fire Diameter – A Comparison of Data Sets

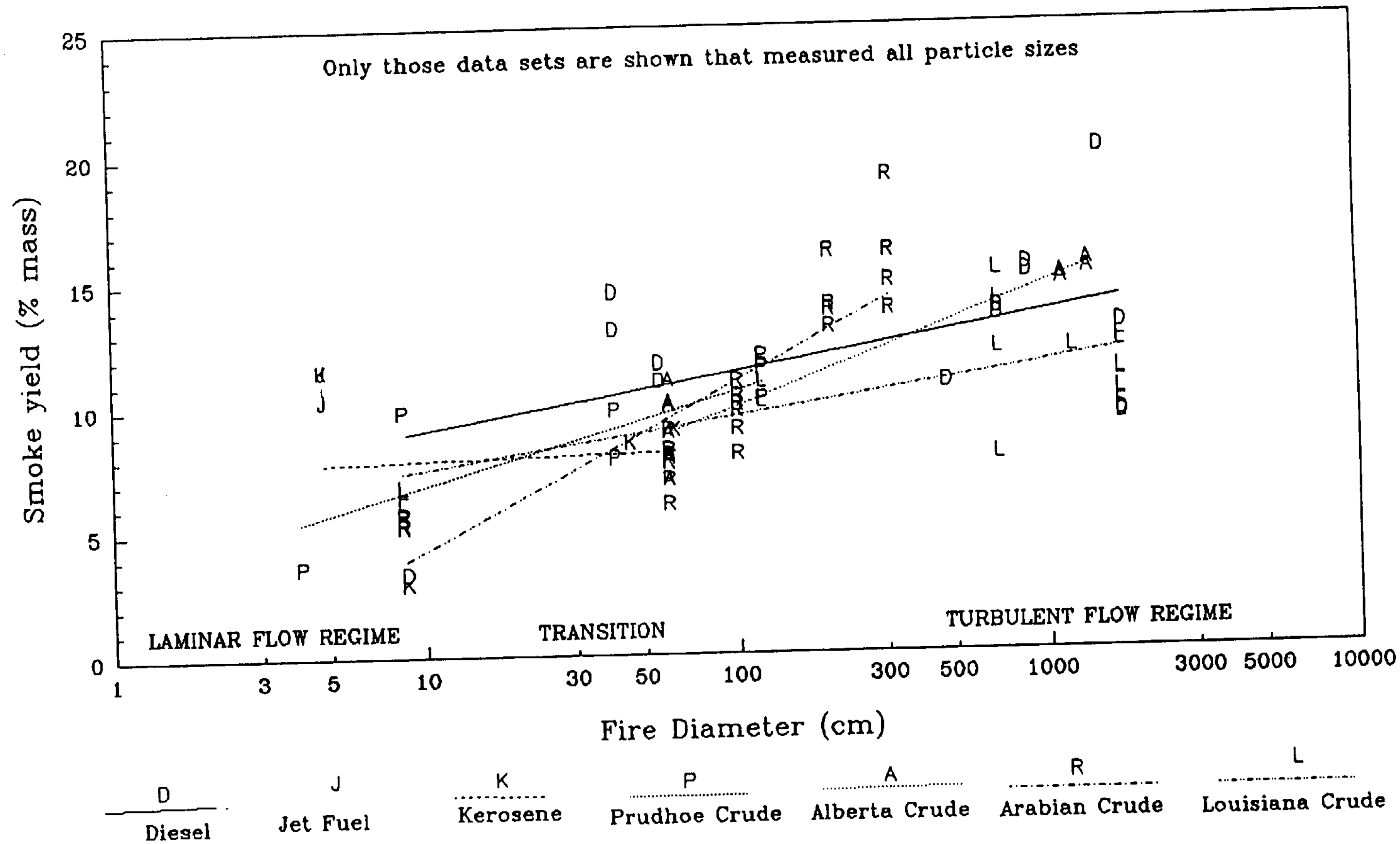

Figure 3: Smoke Yield vs. Fire Diameter – for Different Petroleum Fuels

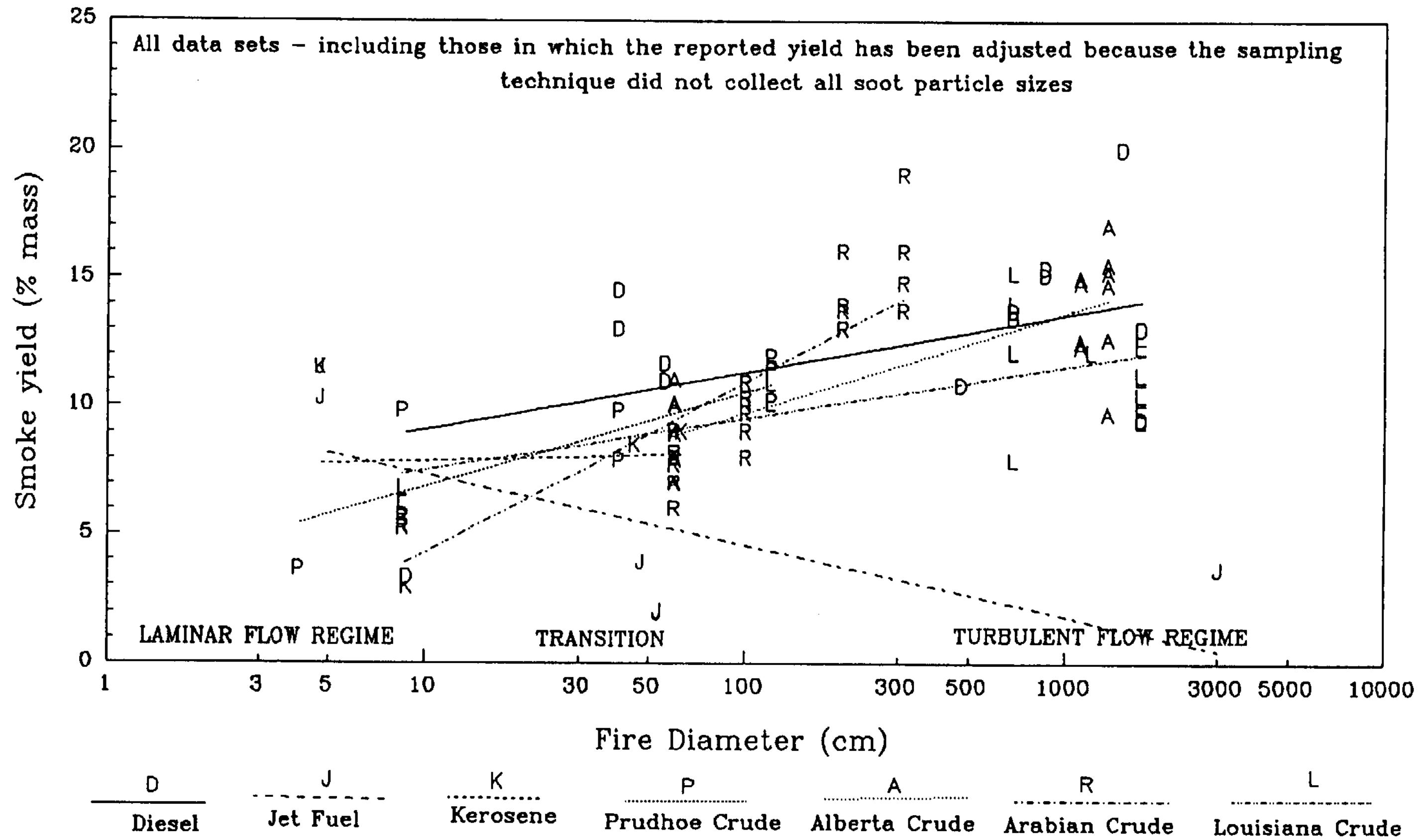

Figure 4: Smoke Yield vs. Fire Diameter – for Different Petroleum Fuels

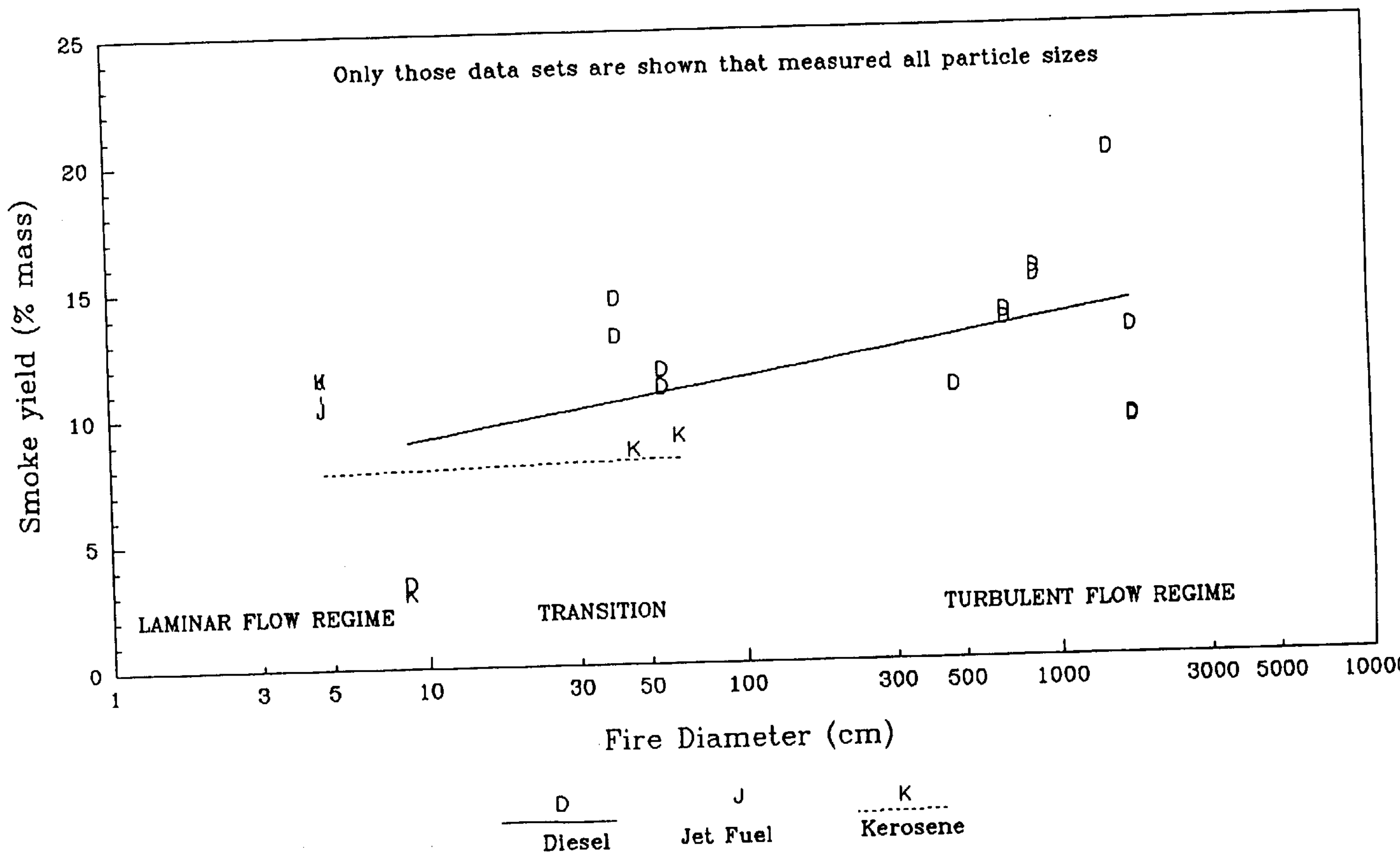

Figure 5: Smoke Yield vs. Fire Diameter – for Different Refined Fuels

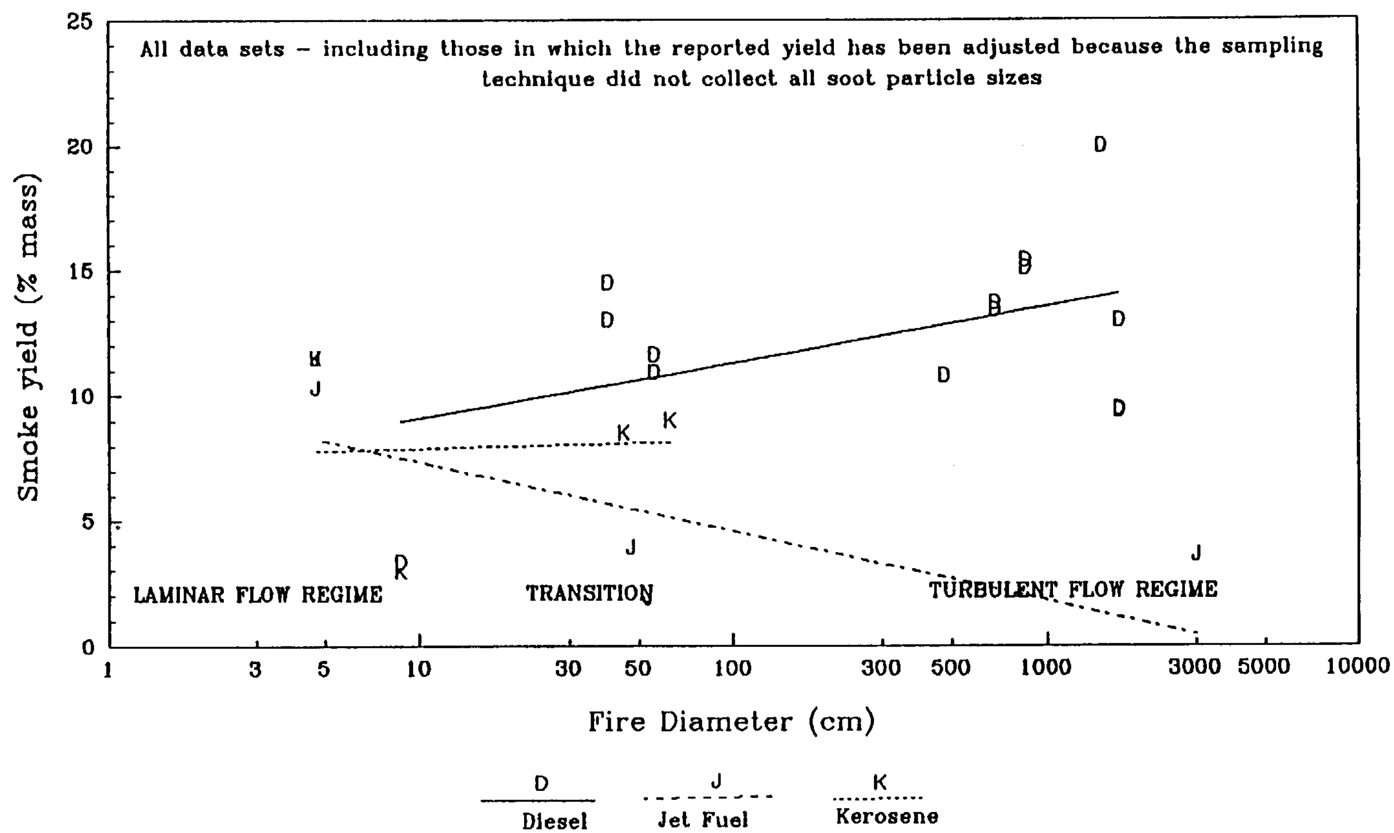

Figure 6: Smoke Yield vs. Fire Diameter – for Different Refined Fuels

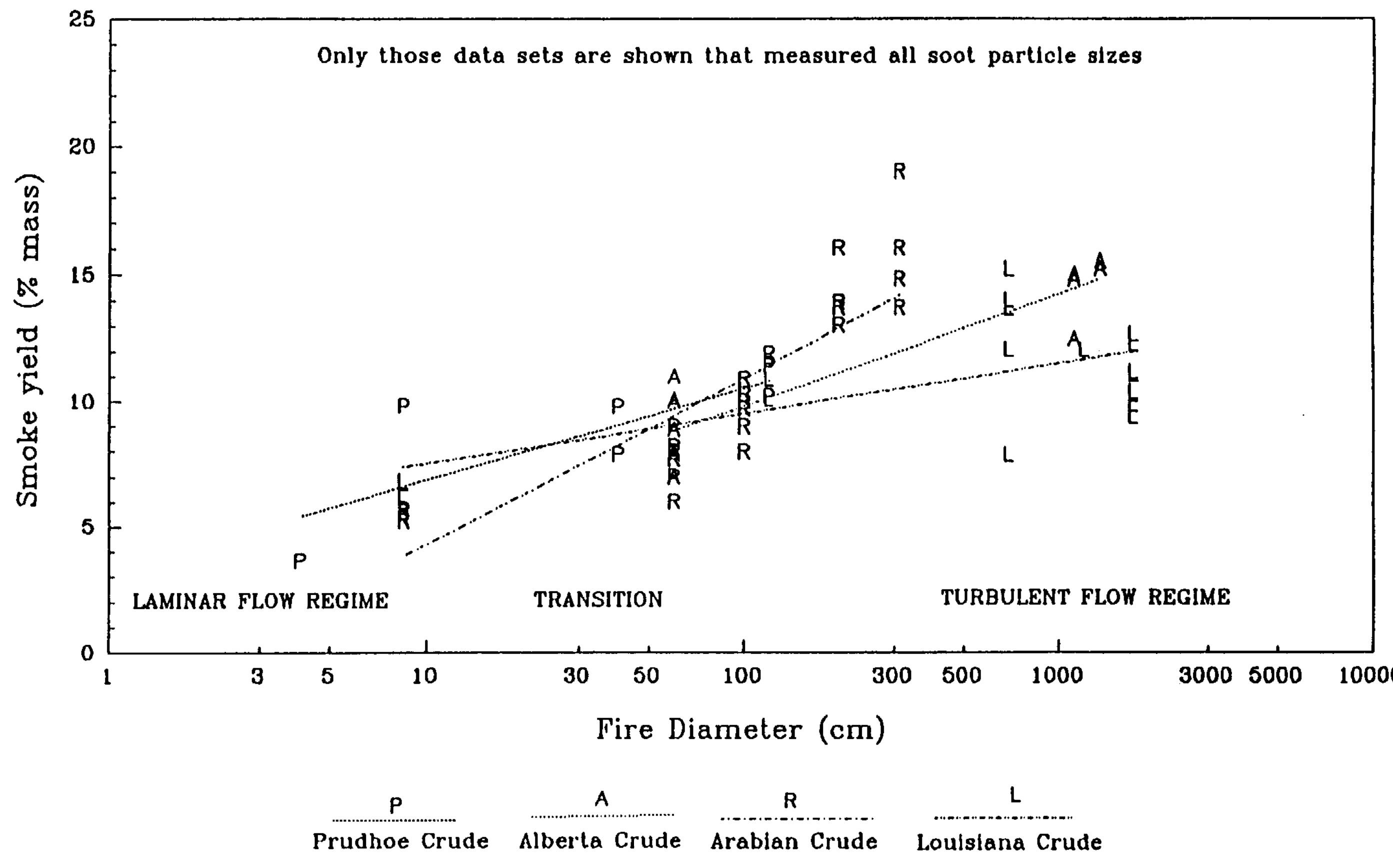

Figure 7: Smoke Yield vs. Fire Diameter – for Different Crude Oils

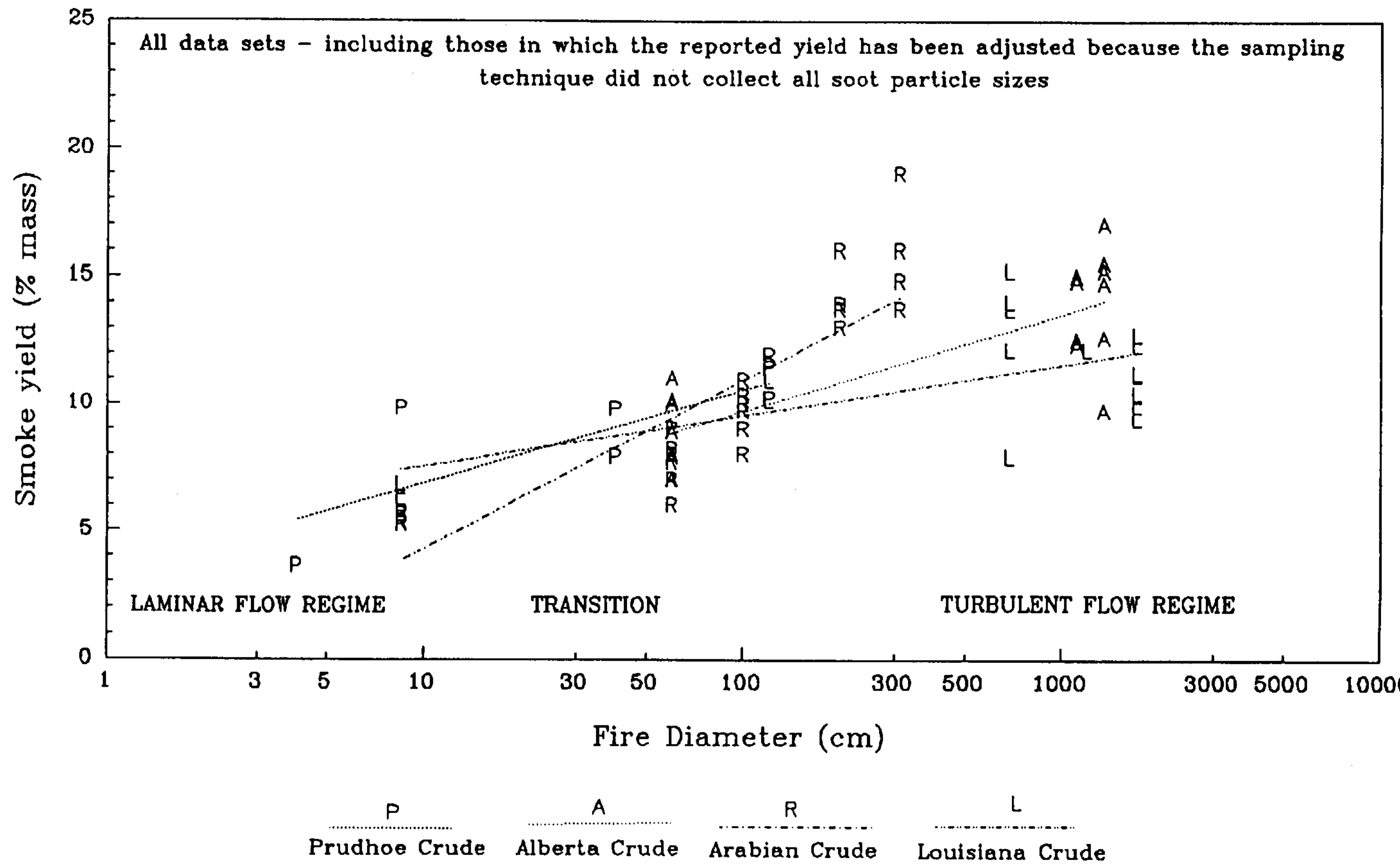

Figure 8: Smoke Yield vs. Fire Diameter – for Different Crude Oils

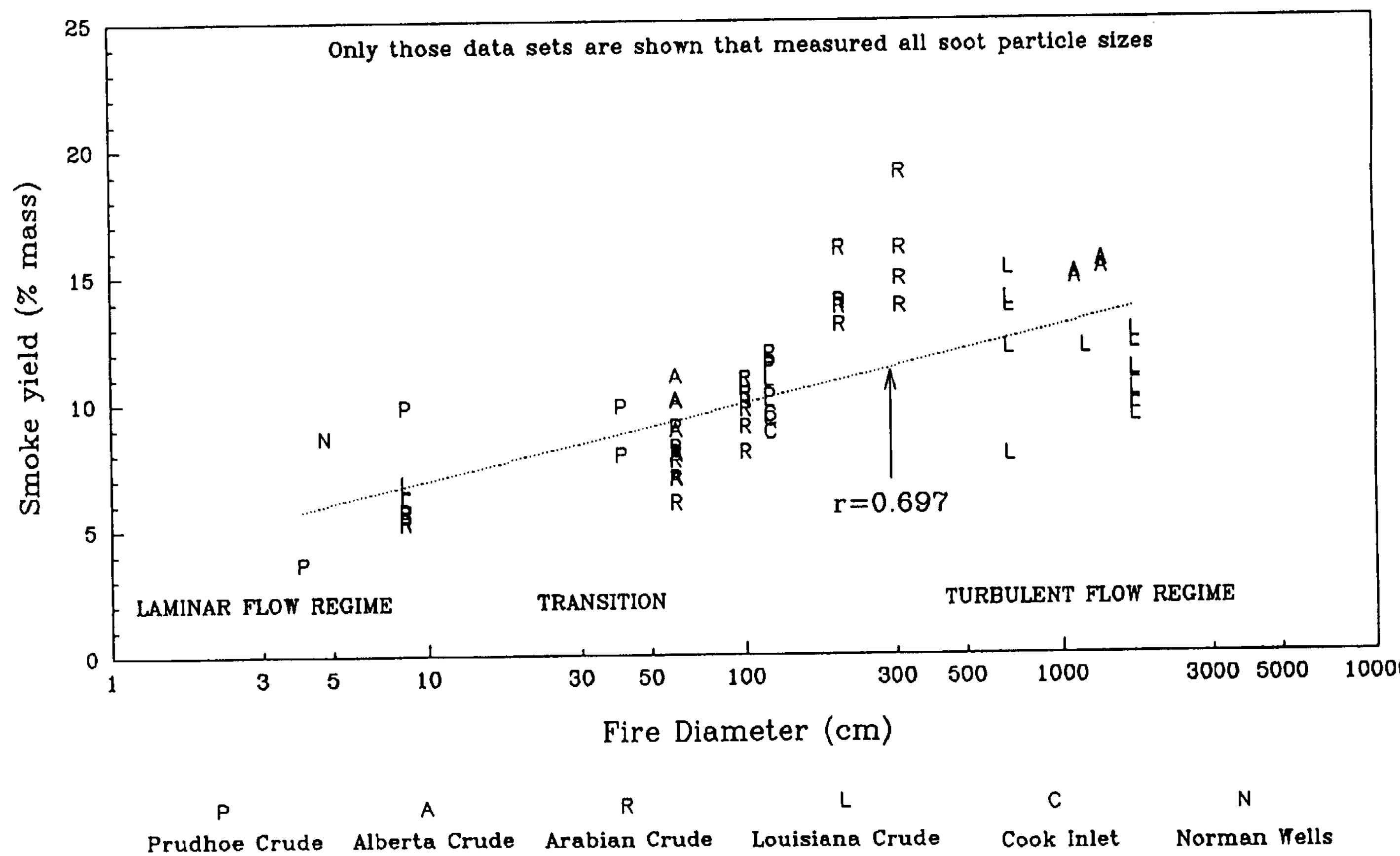

Figure 9: Smoke Yield vs. Fire Diameter – for All Crude Oils

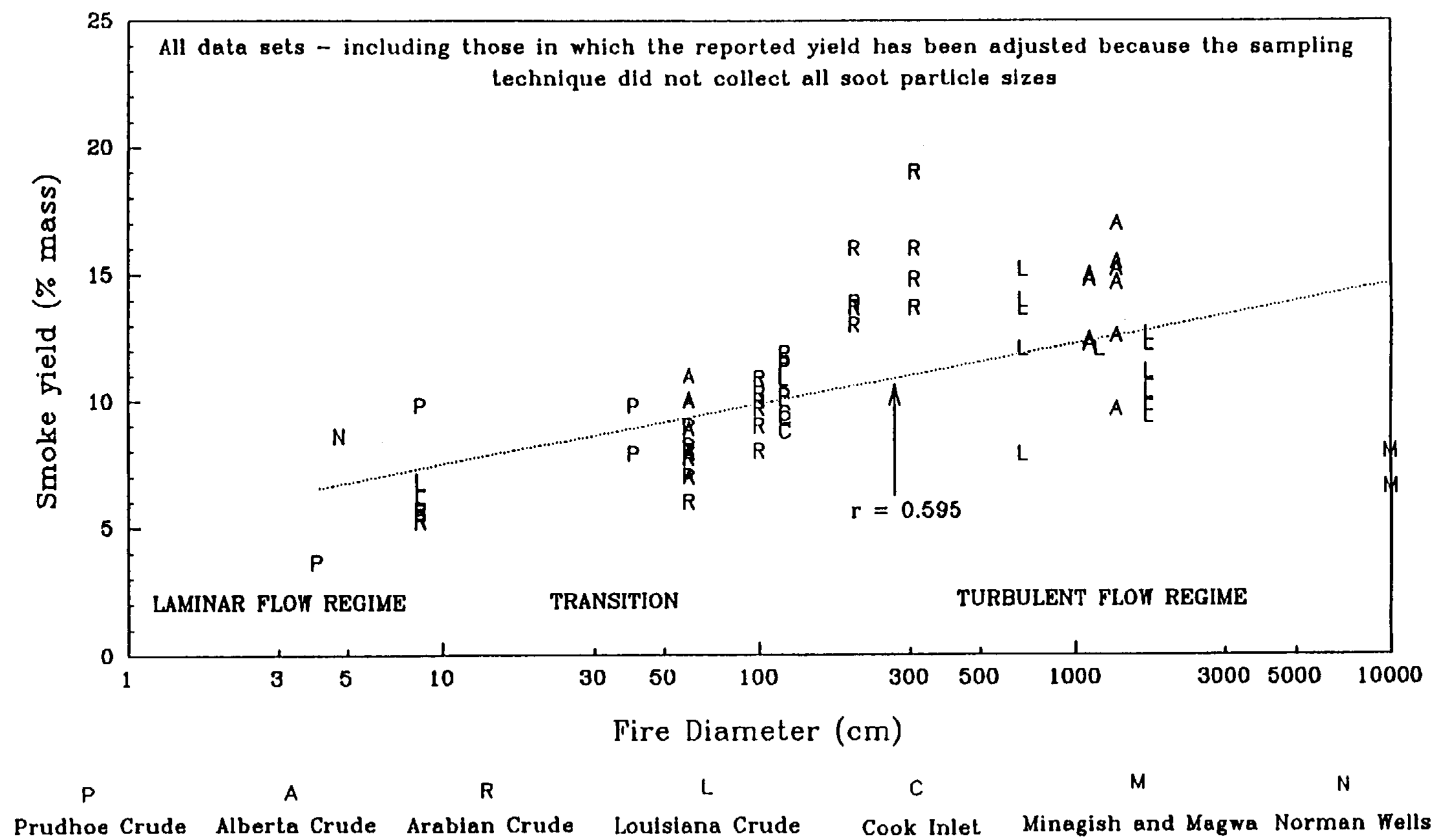

Figure 10: Smoke Yield vs. Fire Diameter – for All Crude Oils

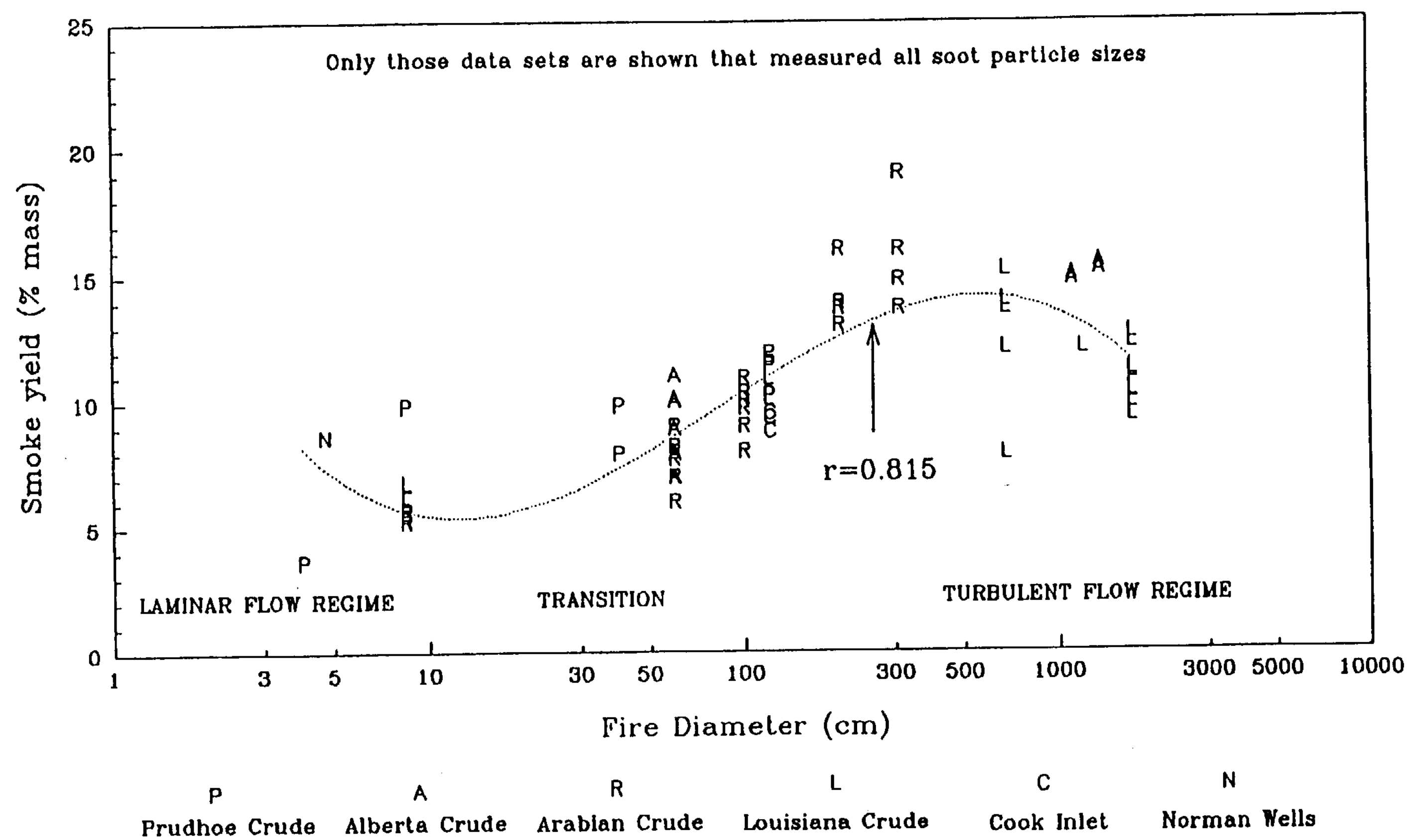

Figure 11: Smoke Yield vs. Fire Diameter – for All Crude Oils

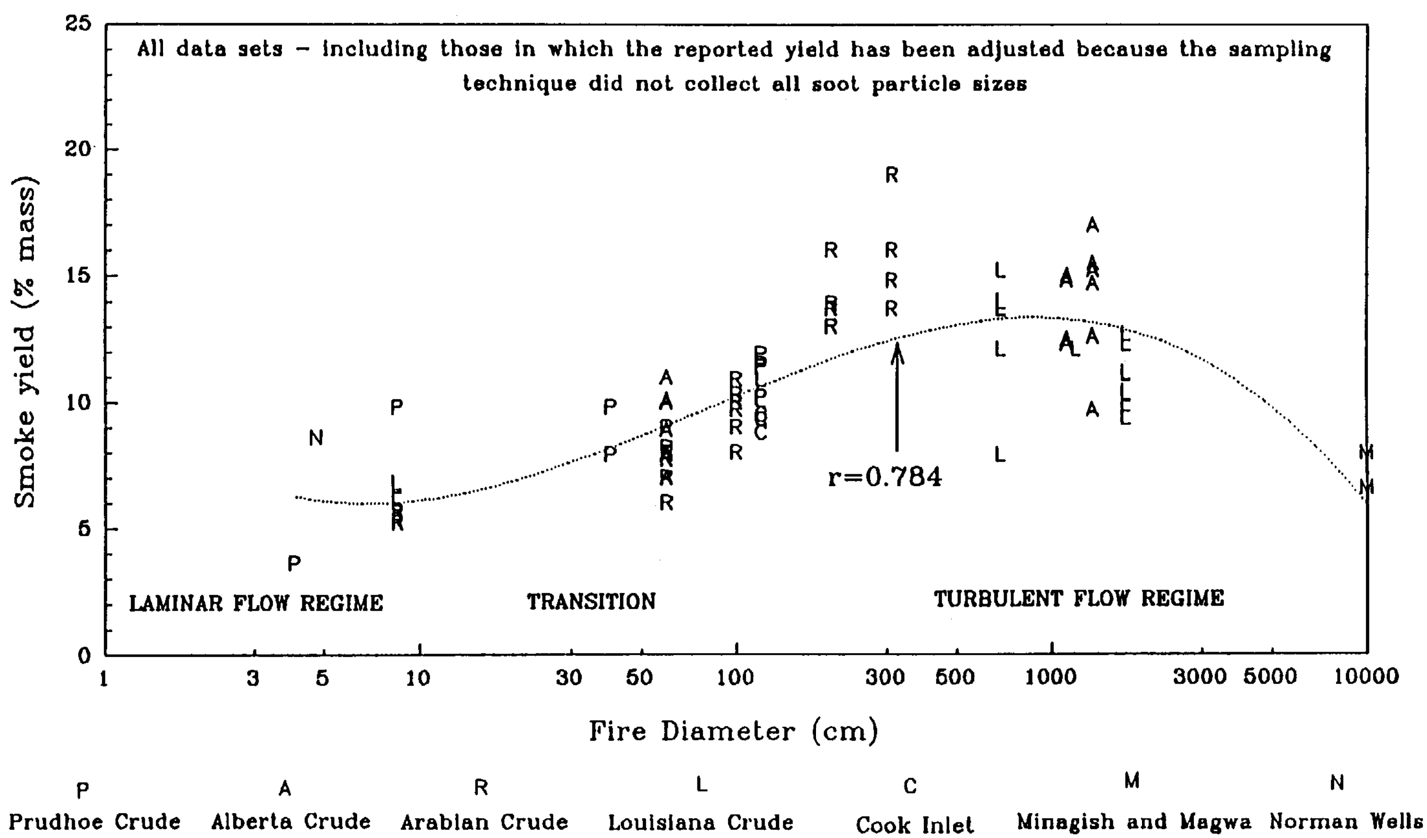

Figure 12: Smoke Yield vs. Fire Diameter - for All Crude Oils

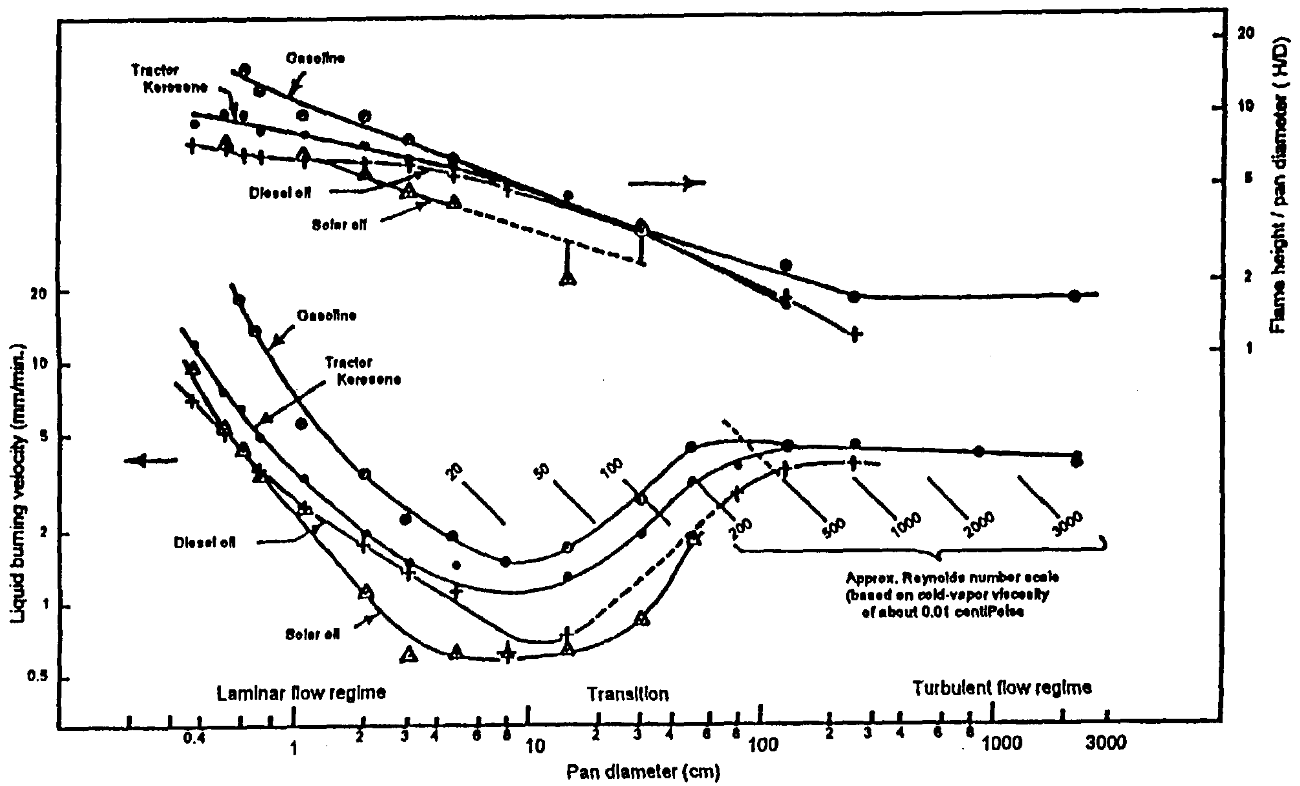

Figure 13: Burning Data (from Blinov and Khudiakov 1959)