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Low-Energy Gamma Ray Attenuation Characteristics of Aviation Fuels

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Summary

Attenuation characteristics of Am^{241} (59.5 keV) gamma rays were investigated in 270 aviation fuel samples (Jet A and Jet A-1) from 76 airports around the world as part of a world-wide study to measure the variability of aviation fuel properties as a function of season and geographical origin. The study began in August 1988 and ended in August 1989. All measurements were made at room temperature, which varied from 20°C to 27°C. Fuel density ρ was measured concurrently with the linear attenuation coefficient μ to provide a measure of mass attenuation coefficient μ/ρ for each test sample. In 43 fuel samples, ρ and μ were measured at more than one room temperature. This provided μ/ρ values for them at several temperatures. The results were found to be independent of the temperature at which μ and ρ were measured. Although individual values of μ and ρ vary considerably from airport to airport as well as from season to season, μ/ρ for all samples is constant at 0.1843 ± 0.0013 cm^2/g. This constancy of μ/ρ for aviation fuels is significant since it indicates that a fuel quantity gauging system based on low-energy gamma ray attenuation will be viable throughout the world.

Introduction

One of the outstanding problems in the aviation industry relates to the fuel quantity gauging (FQG) systems aboard aircraft. All current aircraft FQG systems are based on the old capacitance gauges which reportedly suffer from frequent fouling and electrical noise problems. We recently demonstrated the feasibility of a nuclear gauge for fuel-quantity measurement aboard the aircraft (ref. 1). The proposed nuclear fuel gauge is based on the attenuation of low-energy gamma rays in the fuel column between a collimated radiation source and a collimated colinear detector. Our modeling studies with weak Am^{241} (59.5 keV) radiation sources indicated that it is possible to continuously monitor the fuel quantity in the aircraft tanks to an accuracy of better than 1 percent.

The Airlines Electronic Engineering Committee (AEEC) took our proposal under advisement and suggested that we participate in a study to measure Am^{241} (59.5 keV) gamma ray attenuation coefficients in commercial aviation fuel samples collected from all the major airports in the world over a period of 1 year (refs. 2 to 4). This study would show how fuel mass attenuation characteristics vary as a function of the season and the geographical origin of the samples. If the nuclear fuel gauge is to function reliably, the mass attenuation coefficient values for all fuels must remain essentially constant for all seasons. This paper reports the final results of that study.

Symbols

B_n	height of wing fuel compartment, $n = 1$ to 14
SL	source-detector separation
T	room temperature
μ	linear attenuation coefficient
ρ	density

Experimental Procedure

The monitoring system for measuring fuel attenuation characteristics is made up of a highly collimated 10-μCi Am^{241} gamma ray source and a 5.1-cm-diameter by 5.1-cm-thick NaI(Tl) crystal mounted on a high-gain photomultiplier. We selected Am^{241} as the radiation source because of its long half-life (458 years) and low energy (59.5 keV). The source and the detector assembly are separated by a 5.1-cm-diameter by 10.2-cm-long glass test cell. Figure 1 shows the schematic diagram of the experimental system. The number of photons arriving at the detector I_x depends on the composition of the fuel in the test cell:

$$I_x = I_o e^{-\mu x} \tag{1}$$

where I_o is the number of photons incident on the fuel column of length x and linear attenuation coefficient μ. By using a well-known medium in the test cell—such as air or distilled water—we can determine the value of I_o from the measured value of I_x. Once I_o is determined for a fixed source-detector assembly, I_x becomes the critical measurable parameter in the fuel-quantity study. An independent measurement of the density ρ of the test fuel, coupled with μ determined from equation (1), then permits a direct computation of the mass attenuation coefficient μ/ρ of the sample. This value is expected to be independent of temperature for a given test sample. Further details of the experimental procedure and analysis techniques can be found in reference 5.

The gain stability tests of the spectroscopic measurement system were conducted by monitoring the "air" spectra every day *before* and *after* the test sample attenuation measurements. The channel numbers of the centroids of the *before* and *after* air spectra were always found to agree within ±0.5 throughout the course of this study. If the average channel number of these air spectrum centroids differed from the initial value by more than ±1.0, the photomultiplier bias was adjusted to bring it back to the initial channel number of 331.5. Figure 2 shows the location of air centroid during the entire course of this study. The photomultiplier voltage had to be adjusted only four times during the entire study. The voltage changes required were less than ±0.5 V. The original bias on the photomultiplier was 990.0 V.

Experimental Results and Discussion

The AEEC arranged to provide fuel samples from international airports all over the world over a period of 12 months starting in August 1988. All fuel samples were designated Jet A (or Jet A-1) by the participating airlines. Figure 3 shows the global distribution of the airports sampled. Samples were received from various airports according to the following schedule:

Season	Shipping schedule
Summer 1988	Before August 31, 1988
Fall 1988	Before November 30, 1988
Winter 1988/1989	Before February 28, 1989
Spring 1989	Before May 31, 1989

For convenience of data interpretation and management, the world has been divided into three regions: region I (North America), region II (Europe), and region III (all other areas). Tables I(a), I(b), and I(c) list international airports sampled in the three regions. Tables II(a), II(b), and II(c) list airlines that supplied samples from these airports.

A total of 270 aviation fuel samples were received during this study. The density ρ and linear attenuation coefficient μ for Am^{241} (59.5 keV) gamma rays were measured for each sample at room temperature T to assess the fuel composition variability and its impact on the proposed nuclear fuel gauge. Measurements were made twice for each sample and the average values of ρ, μ, and μ/ρ were calculated. If the individual values differed by more than 1 percent, the measurements were repeated at least twice to give a final set of average values for that sample. Average values of ρ, μ, and μ/ρ for all samples are summarized in table III. Since room temperature ranged from 20°C to 27°C, it was necessary that the density values be normalized to a standard temperature for comparison purposes. We have selected 24°C as the standard temperature since the largest number of density and linear attenuation coefficient measurements (75 out of 270) were made at this temperature.

Normalized density ρ_{24} was calculated as follows:

$$\rho_{24} = \rho_T + \overline{\frac{d\rho}{dT}}\Delta T \qquad (2)$$

where

T room temperature

$\overline{\frac{d\rho}{dT}}$ average value of $\frac{d\rho}{dT}$ measured for 43 fuel samples (its value is -0.0014 ± 0.0003 gm/cm^3 per 1°C)[1]

ΔT $= T - 24°C$

The corresponding normalized linear attenuation coefficient μ_{24} was calculated as follows:

$$\left.\begin{aligned} \frac{\mu_{24}}{\rho_{24}} &= \frac{\mu_T}{\rho_T} = (\mu/\rho)_T \\ &= \frac{\mu}{\rho}^{(2)} \\ \mu_{24} &= \frac{\mu}{\rho}\rho_{24} \end{aligned}\right\} \qquad (3)$$

Figures 6 and 7 show ρ_{24} and μ/ρ for the three regions for different seasons. In some cases more than one sample was received from an airport in the same season. These samples have been treated as independent samples, with their own fuel ID numbers. Also, it should be noted that the sample numbers on the X-axes in these figures are not the fuel ID numbers. The correlation between these sample numbers and their fuel ID numbers is summarized in table V. Since there is no observed trend in ρ or μ/ρ as a function of season or geographical origin, the sample numbers are of interest for bookkeeping purposes only. Figures 8(a) and 8(b) show values of ρ_{24} and μ/ρ for all samples (i.e., regardless of the season). It is obvious from the data summarized in table III and illustrated in figures 6 to 8 that there is considerable variation in ρ_{24} and μ_{24}. However, μ/ρ for all fuel samples is essentially constant at 0.1843 ± 0.0013 cm^2/g, regardless of the season and geographical origin. This result confirms our original proposition that a nuclear

[1]A summary of $d\rho/dT$ values for the 43 samples in which density and linear attenuation coefficient were measured at more than one temperature is given in table IV. The $d\rho/dT$ values are illustrated in figure 4.

[2]From the data summarized in table III and illustrated in figure 5, it is evident μ/ρ is independent of temperature (constant for a given fuel sample), i.e., $(\mu/\rho)_T = \mu/\rho$.

fuel gauge of the type discussed in reference 1 is a viable means for measuring fuel quantity onboard all civil aircraft throughout the world.

Figure 9 shows a conceptual nuclear gauge distribution pattern in a Boeing 737 wing tank in flight. A measurement of μ at any counting station when the tank is full should permit a direct determination of fuel mass with full tank. This follows from the experimentally observed fact that $\mu/\rho = 0.1843 \pm 0.0013$ cm^2/g and the fuel tank volume is known. Similarly, a subsequent measurement of residual fuel volume (see ref. 1 for procedural and computational details) should enable a direct determination of fuel mass onboard the aircraft at any time. The proposed fuel quantity gauging system design can be quite robust and stable, requiring minimal attention for extended periods.

Conclusions

We have computed mass attenuation coefficient for Am^{241} (59.5 keV) gamma rays for 270 aviation fuel samples collected from 76 airports around the world. All measurements were made at room temperature, which ranged from 20°C to 27°C. The density ρ and linear attenuation coefficient μ for a test sample were measured concurrently at the same temperature, thereby giving the mass attenuation coefficient μ/ρ at that temperature. As expected, μ/ρ has been found to be independent of the temperature even though ρ and μ are both temperature-dependent parameters. Despite variations in fuel density and linear attenuation coefficient, the mass attenuation coefficient has been found to be constant at 0.1843 ± 0.0013 cm^2/g, regardless of season and geographical origin. This constancy of mass attenuation coefficient for all fuel samples attests to the suitability of a fuel quantity gauge based on attenuation of Am^{241} gamma rays for all civil aircraft.

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References

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Table I. International Airports Providing Samples

(a) Region I (North America)

Location	Airport	Airport code	Airline code[a]
Anchorage, Alaska, U.S.A.	Anchorage International	ANC	AS
Bermuda	Kindley	BDA	BA
Dallas-Fort Worth, Texas, U.S.A.	Dallas-Fort Worth	DFW	AA
Halifax, Nova Scotia, Canada	Halifax International	YHZ	AC
Kansas City, Missouri, U.S.A.	Kansas City International	MCI	TWA
Los Angeles, California, U.S.A.	Los Angeles International	LAX	FT
Memphis, Tennessee, U.S.A.	Memphis International	MEM	FM
Miami, Florida, U.S.A.	Miami International	MIA	BA
Montreal, Quebec, Canada	Dorval	YUL	AC
Montreal, Quebec, Canada	Mirabel	YMX	AC
Nashville, Tennessee, U.S.A.	Nashville Metropolitan	BNA	AA
New York, New York, U.S.A.	John F. Kennedy International	JFK	TWA
New York, New York, U.S.A.	La Guardia	LGA	TWA
Phoenix, Arizona, U.S.A.	Sky Harbor International	PHX	AA
San Francisco, California, U.S.A.	San Francisco International	SFO	BA
San Juan, Puerto Rico	Puerto Rico International	SJU	AA
Seattle, Washington, U.S.A.	Seattle-Tacoma International	SEA	AS
St. Louis, Missouri, U.S.A.	Lambert-St. Louis International	STL	TWA
Toronto, Ontario, Canada	Toronto International	YYZ	AC
Washington, DC, U.S.A.	Dulles International	IAD	AA
Washington, DC, U.S.A.	National	DCA	TWA

[a] Airlines sampled were as follows: AA—American Airlines; AC—Air Canada; AF—Air France; AS—Alaska Airlines; BA—British Airways; FM—Federal Express; FT—Flying Tigers; KLM—Royal Dutch Airlines; QF—Qantas Airways; SA—South African Airways; SR—Swissair; SV—Saudi Arabian Airlines; TWA—Trans World Airlines.

Table I. Continued

(b) Region II (Europe)

Location	Airport	Airport code	Airline code[a]
Amsterdam, Netherlands	Schiphol	AMS	KLM
Athens, Greece	Hellinikon	ATH	AF
West Berlin, West Germany	Tegel	TXL	AF
Brussels, Belgium	National	BRU	FT
Copenhagen, Denmark	Copenhagen	CPH	BA
Dublin, Ireland	Dublin	DUB	BA
Dusseldorf, West Germany	Dusseldorf	DUS	BA
Geneva, Switzerland	Geneva	GVA	SR
Hamburg, West Germany	Hamburg	HAM	BA
Helsinki, Finland	Helsinki-Vantaa	HEL	BA
Lisbon, Portugal	Lisbon	LIS	AF
London, England	Gatwick	LGW	BA
London, England	Heathrow	LHR	BA
Madrid, Spain	Barajas	MAD	AF
Milan, Italy	Linate	LIN	AF
Moscow, USSR	Sheremetyevo	SVO	AF
Munich, West Germany	Riem	MUC	BA
Nice, France	Côte D'Azur	NCE	AF
Oslo, Norway	Fornebu	FBU	BA
Paris, France	Charles de Gaulle	CDG	BA
Paris, France	Orly	ORY	AF
Rome, Italy	Leonardo da Vinci International	FCO	AF
Stockholm, Sweden	Arlanda	ARN	BA
Toulouse, France	Blagnac	TLS	AF
Vienna, Austria	Vienna (Schwechat)	VIE	BA
Zurich, Switzerland	Zurich	ZRH	SR

[a] Airlines sampled were as follows: AA—American Airlines; AC—Air Canada; AF—Air France; AS—Alaska Airlines; BA—British Airways; FM—Federal Express; FT—Flying Tigers; KLM—Royal Dutch Airlines; QF—Qantas Airways; SA—South African Airways; SR—Swissair; SV—Saudi Arabian Airlines; TWA—Trans World Airlines.

Table I. Concluded

(c) Region III (All other areas)

Location	Airport	Airport code	Airline code[a]
Adelaide, Australia	Adelaide	ADL	QF
Auckland, New Zealand	Auckland International	AKL	BA
Bangkok, Thailand	Bangkok International	BKK	BA
Beijing, China	Capital	PEK	AF
Bombay, India	Bombay	BOM	BA
Brisbane, Australia	Brisbane International	BNE	QF
Buenos Aires, Argentina	Ministro Pistarini-eze	BUE	AF
Cairo, Egypt	Cairo International	CAI	AF
Caracas, Venezuela	Simon Bolivar International	CCS	AF
Cayenne, French Guiana	Rochambeau	CAY	AF
Dhahran, Saudi Arabia	Dhahran International	DAH	SV
Delhi, India	Indira Gandhi International	DEL	BA
Istanbul, Turkey	Istanbul	IST	BA
Jeddah, Saudi Arabia	King Abdulaziz International	JED	SV
Johannesburg, South Africa	Jan Smuts	JNB	SA
Karachi, Pakistan	Karachi	KHI	BA
Kowloon, Hong Kong	Hong Kong	HKG	BA
Kuala Lampur, Malaysia	Kuala Lampur International	KUL	BA
Melbourne, Australia	Melbourne	MEL	QF
Mexico City, Mexico	Benito Juárez International	MEX	AF
Mombasa, Kenya	MOI International	MBA	SR
Nairobi, Kenya	Jomo Kenyatta International	NBO	BA
Osaka, Japan	Osaka International	OSA	AF
Perth, Australia	Perth	PER	QF
Rio de Janeiro, Brazil	Rio de Janeiro International	GIG	AF
Riyadh, Saudi Arabia	King Khalid	RUH	SV
Sydney, Australia	Kingsford Smith	SYD	QF
Tel Aviv, Israel	Ben Gurion	TLV	BA
Tokyo, Japan	Narita	NRT	AF

[a]Airlines sampled were as follows: AA—American Airlines; AC—Air Canada; AF—Air France; AS—Alaska Airlines; BA—British Airways; FM—Federal Express; FT—Flying Tigers; KLM—Royal Dutch Airlines; QF—Qantas Airways; SA—South African Airways; SR—Swissair; SV—Saudi Arabian Airlines; TWA—Trans World Airlines.

Table II. Participating Airlines

[Numbers indicate the number of 2-liter samples taken during year]

(a) Region I (North America)

Location	Airport code	Air Canada	Alaska Airlines	Flying Tigers	TWA	Federal Express	British Airways	American Airlines
Anchorage	ANC		2					
Bermuda	BDA						4	
Dallas	DFW							1
Halifax	YHZ	3						
Kansas City	MCI				4			
Los Angeles	LAX			2				
Memphis	MEM					3		
Miami	MIA						4	
Montreal	YMX	3						
Montreal	YUL	3						
Nashville	BNA							4
New York	JFK				4			
New York	LGA				4			
Phoenix	PHX							4
San Francisco	SFO						3	
San Juan	SJU							4
Seattle	SEA		3					
St. Louis	STL				4			
Toronto	YYZ	3						
Washington	IAD							3
Washington	DCA				4			

Table II. Continued

(b) Region II (Europe)

Location	Airport code	British Airways	Air France	KLM	Swissair	Flying Tigers
Amsterdam, Netherlands	AMS			4		
Athens, Greece	ATH		4			
West Berlin, West Germany	TXL		4			
Brussels, Belgium	BRU					2
Copenhagen, Denmark	CPH	4				
Dublin, Ireland	DUB	4				
Dusseldorf, West Germany	DUS	4				
Geneva, Switzerland	GVA				3	
Hamburg, West Germany	HAM	8				
Helsinki, Finland	HEL	4				
Lisbon, Portugal	LIS		4			
London, England	LGW	4				
London, England	LHR	3				
Madrid, Spain	MAD		4			
Milan, Italy	LIN		4			
Moscow, USSR	SVO		4			
Munich, West Germany	MUC	4				
Nice, France	NCE		4			
Oslo, Norway	FBU	4				
Paris, France	CDG	4				
Paris, France	ORY		4			
Rome, Italy	FCO		4			
Stockholm, Sweden	ARN	4				
Toulouse, France	TLS		4			
Vienna, Austria	VIE	4				
Zurich, Switzerland	ZRH				3	

Table II. Concluded

(c) Region III (All other areas)

Location	Airport code	British Airways	Qantas Airways	Saudi Arabian Airlines	Air France	South African Airways	Flying Tigers	Swissair
Adelaide, Australia	ADL		3					
Auckland, New Zealand	AKL	4						
Bangkok, Thailand	BKK	3						
Beijing, China	PEK				4			
Bombay, India	BOM	4						
Brisbane, Australia	BNE		3					
Buenos Aires, Argentina	BUE				4			
Cairo, Egypt	CAI				4			
Caracas, Venezuela	CCS				4			
Cayenne, French Guiana	CAY				4			
Dhahran, Saudi Arabia	DAH			2				
Delhi, India	DEL	2						
Istanbul, Turkey	IST	4						
Jeddah, Saudi Arabia	JED			2				
Johannesburg, South Africa	JNB					4		
Karachi, Pakistan	KHI	4						
Kowloon, Hong Kong	HKG	3						
Kuala Lampur, Malaysia	KUL	4						
Melbourne, Australia	MEL		3					
Mexico City, Mexico	MEX				4			
Mombasa, Kenya	MBA							4
Nairobi, Kenya	NBO	1						
Osaka, Japan	OSA				4			
Perth, Australia	PER		3					
Rio de Janeiro, Brazil	GIG				4			
Riyadh, Saudi Arabia	RUH			2				
Sydney, Australia	SYD		3					
Tel Aviv, Israel	TLV	4						
Tokyo, Japan	NRT				4			

Table III. Summary of Results of All Fuel Samples

Fuel ID number	Airline (airport)	ρ, g/cm^3 (T, °C)	μ, 1/cm (T, °C)	μ/ρ, cm^2/g	ρ_{24}, g/cm^3	μ_{24}, 1/cm
1	TWA (MCI)	0.8022 (25.0)	0.1475 ± 0.0016 (25.0)	0.1833 ± 0.0015	0.8036	0.1473 ± 0.0012
2	SR (ZRH)	.7880 (25.0)	.1460 ± .0015 (25.0)	.1852 ± .0014	.7896	.1462 ± .0011
3	SR (GVA)	.7871 (25.0)	.1454 ± .0015 (25.0)	.1851 ± .0015	.7885	.1460 ± .0012
4	SR (MBA)	.7798 (25.0)	.1439 ± .0015 (25.0)	.1852 ± .0024	.7776	.1440 ± .0019
5	AC (YHZ)	.7913 (25.0)	.1450 ± .0015 (25.0)	.1831 ± .0013	.7931	.1452 ± .0010
6	TWA (JFK)	.8094 (23.5)	.1485 ± .0016 (23.5)	.1830 ± .0018	.8091	.1481 ± .0015
7	AA (BNA)	.8057 (24.0)	.1483 ± .0016 (24.0)	.1849 ± .0017	.8056	.1490 ± .0014
8	AA (PHX)	.8158 (25.0)	.1507 ± .0016 (25.0)	.1842 ± .0015	.8169	.1505 ± .0012
9	AC (YMX)	.7928 (25.0)	.1454 ± .0015 (25.0)	.1838 ± .0014	.7943	.1460 ± .0011
10	AC (YUL)	.7896 (25.0)	.1463 ± .0015 (25.0)	.1843 ± .0017	.7910	.1458 ± .0013
11	AC (YYZ)	.8006 (25.0)	.1471 ± .0015 (25.0)	.1832 ± .0015	.8019	.1469 ± .0012
12	KLM (AMS)	.7901 (25.0)	.1448 ± .0015 (25.0)	.1842 ± .0017	.7911	.1457 ± .0013
13	TWA (LGA)	.8059 (25.0)	.1478 ± .0016 (25.0)	.1840 ± .0015	.8074	.1486 ± .0012
14	AA (SJU)	.7949 (25.0)	.1475 ± .0016 (25.0)	.1846 ± .0023	.7962	.1470 ± .0018
15	AA (IAD)	.8072 (25.0)	.1493 ± .0016 (25.0)	.1843 ± .0015	.8086	.1490 ± .0012
16	FT (LAX)	.8103 (24.0)	.1506 ± .0016 (24.0)	.1855 ± .0014	.8104	.1503 ± .0011
17	TWA (DCA)	.8053 (24.0)	.1489 ± .0016 (24.0)	.1842 ± .0015	.8052	.1483 ± .0012
18	TWA (STL)	.8047 (24.0)	.1487 ± .0016 (24.0)	.1843 ± .0014	.8048	.1483 ± .0011
19	FM (MEM)	.8090 (24.5)	.1485 ± .0015 (24.5)	.1830 ± .0016	.8084	.1479 ± .0013
20	AS (SEA)	.8175 (22.5)	.1502 ± .0016 (22.5)	.1833 ± .0015	.8154	.1495 ± .0012
21	FT (BRU)	.7896 (25.0)	.1463 ± .0015 (25.0)	.1854 ± .0017	.7918	.1468 ± .0013
22	BA (MIA)	.8050 (25.0)	.1479 ± .0016 (25.0)	.1831 ± .0015	.8065	.1477 ± .0012
23	AS (ANC)	.8042 (25.0)	.1492 ± .0016 (25.0)	.1852 ± .0014	.8058	.1492 ± .0011
24	BA (CPH)	.7846 (25.0)	.1447 ± .0015 (25.0)	.1844 ± .0014	.7858	.1449 ± .0011
25	BA (TLV)	.7913 (25.0)	.1464 ± .0015 (25.0)	.1850 ± .0014	.7923	.1466 ± .0011

Table III. Continued

Fuel ID number	Airline (airport)	ρ, g/cm^3 (T, °C)	μ, 1/cm (T, °C)	μ/ρ, cm^2/g	ρ_{24}, g/cm^3	μ_{24}, 1/cm
26	BA (FBU)	0.7929 (25.0)	0.1467 ± 0.0015 (25.0)	0.1840 ± 0.0021	0.7941	0.1461 ± 0.0017
27	BA (HEL)	.7950 (23.0)	.1474 ± .0015 (23.0)	.1856 ± .0016	.7937	.1473 ± .0013
28	BA (MUC)	.7870 (25.0)	.1464 ± .0015 (25.0)	.1851 ± .0020	.7882	.1459 ± .0016
29	BA (CDG)	.7889 (24.0)	.1461 ± .0015 (24.0)	.1853 ± .0015	.7882	.1461 ± .0012
30	BA (AKL)	.7865 (23.5)	.1452 ± .0015 (23.5)	.1851 ± .0018	.7863	.1455 ± .0014
31	BA (DUB)	.7957 (25.0)	.1472 ± .0016 (25.0)	.1856 ± .0021	.7982	.1481 ± .0017
32	BA (DUS)	.7961 (25.0)	.1479 ± .0016 (25.0)	.1854 ± .0014	.7964	.1477 ± .0011
33	BA (BKK)	.7890 (25.0)	.1467 ± .0015 (25.0)	.1852 ± .0024	.7904	.1464 ± .0019
34	BA (KHI)	.7836 (25.0)	.1456 ± .0015 (25.0)	.1852 ± .0015	.7847	.1453 ± .0012
35	BA (VIE)	.7815 (25.0)	.1437 ± .0015 (25.0)	.1854 ± .0021	.7828	.1451 ± .0016
36	BA (DEL)	.8028 (25.0)	.1480 ± .0016 (25.0)	.1846 ± .0018	.8042	.1485 ± .0014
37	BA (HAM)	.7827 (25.0)	.1444 ± .0015 (25.0)	.1840 ± .0015	.7842	.1443 ± .0012
38	BA (HAM)	.7817 (25.0)	.1447 ± .0015 (25.0)	.1851 ± .0016	.7832	.1450 ± .0013
39	BA (KUL)	.7849 (25.0)	.1442 ± .0015 (25.0)	.1843 ± .0015	.7864	.1449 ± .0012
40	AF (ATH)	.7874 (24.0)	.1464 ± .0015 (24.0)	.1857 ± .0014	.7871	.1462 ± .0011
41	AF (ORY)	.7888 (25.0)	.1460 ± .0015 (25.0)	.1849 ± .0014	.7901	.1461 ± .0011
42	AF (GIG)	.7726 (25.0)	.1432 ± .0015 (25.0)	.1854 ± .0014	.7736	.1434 ± .0011
43	AF (CAI)	.7841 (25.0)	.1459 ± .0015 (25.0)	.1851 ± .0017	.7851	.1453 ± .0013
44	AF (MEX)	.7849 (24.5)	.1456 ± .0015 (24.5)	.1854 ± .0015	.7829	.1451 ± .0012
45	AF (TXL)	.7934 (24.0)	.1463 ± .0015 (24.0)	.1850 ± .0014	.7936	.1460 ± .0011
46	AF (TLS)	.7809 (24.0)	.1437 ± .0015 (24.0)	.1835 ± .0015	.7812	.1434 ± .0012
47	AF (FCO)	.7827 (24.0)	.1450 ± .0015 (24.0)	.1851 ± .0014	.7824	.1448 ± .0011
48	AF (NCE)	.7928 (24.0)	.1460 ± .0015 (24.0)	.1846 ± .0014	.7926	.1463 ± .0011
49	AF (NRT)	.7858 (24.0)	.1451 ± .0015 (24.0)	.1847 ± .0018	.7856	.1451 ± .0014
50	AF (OSA)	.7861 (24.0)	.1451 ± .0015 (24.0)	.1842 ± .0015	.7858	.1447 ± .0012

Table III. Continued

Fuel ID number	Airline (airport)	ρ, g/cm³ (T, °C)	μ, 1/cm (T, °C)	μ/ρ, cm²/g	ρ_{24}, g/cm³	μ_{24}, 1/cm
51	AF (CAY)	0.8176 (24.0)	0.1501 ± 0.0016 (24.0)	0.1836 ± 0.0013	0.8178	0.1501 ± 0.0011
52	AF (LIS)	.7910 (24.0)	.1458 ± .0015 (24.0)	.1849 ± .0015	.7909	.1462 ± .0012
53	AF (LIN)	.7867 (24.0)	.1458 ± .0015 (24.0)	.1854 ± .0018	.7861	.1457 ± .0014
54	AF (BUE)	.7921 (24.0)	.1473 ± .0016 (24.0)	.1856 ± .0015	.7920	.1470 ± .0012
55	AF (SVO)	.7816 (23.5)	.1447 ± .0015 (23.5)	.1854 ± .0019	.7810	.1448 ± .0015
56	AF (CCS)	.8058 (24.0)	.1494 ± .0016 (24.0)	.1848 ± .0015	.8059	.1489 ± .0012
57	BA (AKL)	.7861 (24.0)	.1454 ± .0015 (24.0)	.1853 ± .0017	.7852	.1455 ± .0013
58	AC (YHZ)	.7921 (24.0)	.1468 ± .0016 (24.0)	.1854 ± .0010	.7921	.1469 ± .0008
59	BA (LGW)	.7943 (23.0)	.1461 ± .0015 (23.0)	.1837 ± .0014	.7933	.1457 ± .0011
60	BA (LHR)	.7934 (24.0)	.1471 ± .0016 (24.0)	.1850 ± .0021	.7934	.1468 ± .0017
61	AA (BNA)	.8055 (23.5)	.1494 ± .0016 (23.5)	.1852 ± .0013	.8054	.1492 ± .0010
62	AA (BNA)	.8048 (24.0)	.1489 ± .0016 (24.0)	.1854 ± .0019	.8048	.1492 ± .0015
63	AF (PEK)	.7941 (24.0)	.1471 ± .0015 (24.0)	.1855 ± .0016	.7940	.1473 ± .0013
64	AF (MAD)	.7952 (24.0)	.1473 ± .0016 (24.0)	.1851 ± .0021	.7951	.1472 ± .0017
65	TWA (LGA)	.8081 (22.0)	.1497 ± .0016 (22.0)	.1852 ± .0019	.8056	.1492 ± .0015
66	TWA (JFK)	.8072 (23.0)	.1491 ± .0015 (23.0)	.1852 ± .0023	.8061	.1493 ± .0019
67	BA (CDG)	.7878 (23.0)	.1468 ± .0015 (23.0)	.1855 ± .0023	.7855	.1457 ± .0018
68	BA (HKG)	.7940 (23.5)	.1471 ± .0016 (23.5)	.1853 ± .0018	.7926	.1469 ± .0014
69	BA (ARN)	.7833 (23.5)	.1441 ± .0015 (23.5)	.1848 ± .0018	.7825	.1446 ± .0014
70	BA (MUC)	.7893 (24.0)	.1463 ± .0015 (24.0)	.1848 ± .0015	.7893	.1459 ± .0012
71	BA (IST)	.7807 (21.0)	.1436 ± .0015 (21.0)	.1839 ± .0017	.7795	.1434 ± .0013
72	KLM (AMS)	.7907 (24.0)	.1450 ± .0015 (24.0)	.1849 ± .0020	.7909	.1462 ± .0016
73	BA (CPH)	.7811 (24.0)	.1449 ± .0015 (24.0)	.1849 ± .0016	.7814	.1445 ± .0013
74	AA (PHX)	.8142 (24.0)	.1504 ± .0016 (24.0)	.1849 ± .0014	.8144	.1506 ± .0011
75	BA (TLV)	.7953 (24.0)	.1472 ± .0015 (24.0)	.1853 ± .0013	.7950	.1473 ± .0010

Table III. Continued

Fuel ID number	Airline (airport)	ρ, g/cm^3 (T, °C)	μ, 1/cm (T, °C)	μ/ρ, cm^2/g	ρ_{24}, g/cm^3	μ_{24}, 1/cm
76	BA (FBU)	0.7893 (23.5)	0.1464 ± 0.0015 (23.5)	0.1851 ± 0.0014	0.7890	0.1460 ± 0.0011
77	BA (HEL)	.7870 (24.0)	.1453 ± .0015 (24.0)	.1848 ± .0015	.7873	.1455 ± .0012
78	BA (IST)	.7796 (24.0)	.1452 ± .0015 (24.0)	.1849 ± .0029	.7796	.1441 ± .0023
79	BA (BOM)	.7816 (23.5)	.1447 ± .0015 (23.5)	.1853 ± .0011	.7810	.1447 ± .0009
80	BA (VIE)	.7973 (24.0)	.1479 ± .0016 (24.0)	.1849 ± .0015	.7973	.1474 ± .0012
81	BA (DUS)	.8023 (24.0)	.1479 ± .0015 (24.0)	.1849 ± .0016	.8023	.1483 ± .0013
82	BA (MIA)	.7863 (24.0)	.1461 ± .0015 (24.0)	.1856 ± .0014	.7864	.1460 ± .0011
83	BA (HKG)	.7906 (24.0)	.1457 ± .0015 (24.0)	.1847 ± .0023	.7906	.1460 ± .0018
84	AA (SJU)	.8131 (24.0)	.1508 ± .0016 (24.0)	.1852 ± .0014	.8132	.1506 ± .0011
85	BA (BDA)	.8151 (25.0)	.1501 ± .0016 (25.0)	.1841 ± .0015	.8161	.1502 ± .0012
86	BA (KHI)	.7806 (27.0)	.1439 ± .0015 (27.0)	.1845 ± .0019	.7828	.1444 ± .0015
87	BA (DEL)	.7807 (25.0)	.1444 ± .0015 (25.0)	.1848 ± .0016	.7813	.1444 ± .0013
88	AC (YUL)	.7917 (23.5)	.1461 ± .0015 (23.5)	.1850 ± .0012	.7913	.1464 ± .0009
89	AC (YMX)	.8017 (22.0)	.1477 ± .0016 (22.0)	.1842 ± .0011	.8000	.1474 ± .0009
90	BA (DUB)	.7909 (23.5)	.1458 ± .0015 (23.5)	.1852 ± .0016	.7901	.1463 ± .0013
91	AC (YYZ)	.8017 (23.5)	.1471 ± .0016 (23.5)	.1842 ± .0020	.8006	.1475 ± .0016
92	BA (BDA)	.8167 (23.0)	.1500 ± .0015 (23.0)	.1838 ± .0015	.8148	.1498 ± .0012
93	FM (MEM)	.8050 (23.0)	.1477 ± .0016 (23.0)	.1835 ± .0012	.8043	.1476 ± .0010
94	TWA (MCI)	.8048 (23.5)	.1471 ± .0015 (23.5)	.1831 ± .0018	.8054	.1475 ± .0014
95	TWA (DCA)	.7980 (24.0)	.1477 ± .0016 (24.0)	.1848 ± .0014	.7979	.1475 ± .0011
96	TWA (STL)	.8025 (23.5)	.1471 ± .0016 (23.5)	.1831 ± .0015	.8024	.1469 ± .0012
97	BA (HAM)	.7874 (23.5)	.1446 ± .0015 (23.5)	.1834 ± .0012	.7854	.1440 ± .0009
98	BA (HAM)	.7843 (24.0)	.1437 ± .0015 (24.0)	.1831 ± .0013	.7846	.1437 ± .0010
99	BA (HAM)	.7851 (24.0)	.1436 ± .0015 (24.0)	.1832 ± .0018	.7850	.1438 ± .0014
100	BA (BKK)	.7944 (23.0)	.1465 ± .0015 (23.0)	.1835 ± .0024	.7932	.1456 ± .0019

Table III. Continued

Fuel ID number	Airline (airport)	ρ, g/cm^3 (T, °C)	μ, 1/cm (T, °C)	μ/ρ, cm^2/g	ρ_{24}, g/cm^3	μ_{24}, 1/cm
101	BA (BOM)	0.7847 (24.0)	0.1441 ± 0.0015 (24.0)	0.1833 ± 0.0017	0.7848	0.1439 ± 0.0013
102	SR (MBA)	.7798 (24.0)	.1432 ± .0015 (24.0)	.1831 ± .0019	.7797	.1428 ± .0015
103	SR (ZRH)	.7891 (23.0)	.1446 ± .0015 (23.0)	.1831 ± .0014	.7879	.1443 ± .0011
104	SR (GVA)	.7894 (23.0)	.1450 ± .0015 (23.0)	.1832 ± .0016	.7891	.1446 ± .0013
105	AA (IAD)	.8051 (23.0)	.1475 ± .0016 (23.0)	.1832 ± .0011	.8039	.1473 ± .0009
106	AS (ANC)	.8050 (24.0)	.1472 ± .0016 (24.0)	.1831 ± .0013	.8051	.1474 ± .0010
107	AF (PEK)	.7771 (23.0)	.1440 ± .0015 (23.0)	.1840 ± .0019	.7758	.1427 ± .0015
108	AF (SVO)	.9106 (23.0)	.1666 ± .0017 (23.0)	.1832 ± .0013	.9087	.1665 ± .0012
109	AF (LIN)	.7882 (23.0)	.1443 ± .0015 (23.0)	.1833 ± .0014	.7869	.1442 ± .0011
110	AF (NRT)	.7813 (24.0)	.1434 ± .0015 (24.0)	.1832 ± .0013	.7815	.1432 ± .0010
111	AF (GIG)	.7891 (24.0)	.1444 ± .0015 (24.0)	.1835 ± .0020	.7891	.1448 ± .0016
112	AF (ATH)	.7916 (23.0)	.1461 ± .0015 (23.0)	.1838 ± .0016	.7903	.1453 ± .0013
113	AF (MAD)	.7937 (23.5)	.1459 ± .0015 (23.5)	.1836 ± .0021	.7928	.1456 ± .0017
114	AF (TXL)	.7862 (23.0)	.1441 ± .0015 (23.0)	.1846 ± .0020	.7851	.1449 ± .0016
115	AF (CAI)	.7878 (23.0)	.1443 ± .0015 (23.0)	.1831 ± .0013	.7865	.1440 ± .0010
116	AF (CAY)	.8171 (24.0)	.1498 ± .0016 (24.0)	.1830 ± .0015	.8171	.1495 ± .0012
117	AF (TLS)	.7823 (23.0)	.1435 ± .0015 (23.0)	.1835 ± .0014	.7811	.1433 ± .0011
118	AF (LIS)	.7899 (23.0)	.1453 ± .0015 (23.0)	.1840 ± .0013	.7885	.1451 ± .0010
119	AF (OSA)	.7883 (23.0)	.1439 ± .0015 (23.0)	.1831 ± .0015	.7871	.1441 ± .0012
120	AF (ORY)	.7882 (23.0)	.1464 ± .0015 (23.0)	.1856 ± .0012	.7868	.1460 ± .0009
121	AF (NCE)	.7872 (23.0)	.1437 ± .0015 (23.0)	.1830 ± .0015	.7858	.1438 ± .0012
122	AF (FCO)	.7866 (23.5)	.1441 ± .0015 (23.5)	.1829 ± .0019	.7859	.1437 ± .0015
123	AF (BUE)	.7892 (23.0)	.1462 ± .0016 (23.0)	.1849 ± .0015	.7878	.1457 ± .0012
124	AF (MEX)	.7870 (23.0)	.1454 ± .0015 (23.0)	.1851 ± .0015	.7858	.1455 ± .0012
125	AF (CCS)	.7926 (23.0)	.1454 ± .0015 (23.0)	.1846 ± .0018	.7912	.1461 ± .0014

Table III. Continued

Fuel ID number	Airline (airport)	ρ, g/cm^3 (T, °C)	μ, 1/cm (T, °C)	μ/ρ, cm^2/g	ρ_{24}, g/cm^3	μ_{24}, 1/cm
126	BA (KUL)	0.7903 (23.0)	0.1450 ± 0.0015 (23.0)	0.1841 ± 0.0015	0.7889	0.1452 ± 0.0012
127	BA (LGW)	.7940 (23.0)	.1454 ± .0015 (23.0)	.1836 ± .0014	.7926	.1455 ± .0011
128	AA (DFW)	.8115 (23.0)	.1479 ± .0016 (23.0)	.1839 ± .0021	.8102	.1490 ± .0017
129	QF (SYD)	.7964 (23.0)	.1455 ± .0015 (23.0)	.1831 ± .0014	.7951	.1456 ± .0011
130	QF (MEL)	.7854 (22.5)	.1436 ± .0015 (22.5)	.1831 ± .0013	.7866	.1440 ± .0010
131	QF (BNE)	.7870 (23.0)	.1436 ± .0015 (23.0)	.1838 ± .0020	.7858	.1444 ± .0016
132	QF (PER)	.7893 (23.0)	.1454 ± .0015 (23.0)	.1840 ± .0014	.7880	.1450 ± .0011
133	QF (ADL)	.7806 (23.5)	.1440 ± .0015 (23.5)	.1839 ± .0017	.7797	.1434 ± .0013
134	FT (BRU)	.7886 (24.0)	.1453 ± .0015 (24.0)	.1838 ± .0016	.7887	.1450 ± .0013
135	BA (LHR)	.7935 (23.0)	.1455 ± .0015 (23.0)	.1840 ± .0015	.7919	.1457 ± .0012
136	AA (BNA)	.8057 (23.0)	.1483 ± .0016 (23.0)	.1835 ± .0024	.8036	.1475 ± .0019
137	BA (FBU)	.7911 (23.0)	.1450 ± .0015 (23.0)	.1834 ± .0013	.7897	.1448 ± .0010
138	BA (TLV)	.7962 (23.0)	.1457 ± .0015 (23.0)	.1836 ± .0014	.7948	.1459 ± .0011
139	BA (IST)	.7782 (23.0)	.1431 ± .0015 (23.0)	.1836 ± .0014	.7772	.1427 ± .0011
140	BA (CPH)	.7940 (21.5)	.1455 ± .0015 (21.5)	.1832 ± .0013	.7906	.1448 ± .0010
141	FT (LAX)	.8204 (24.0)	.1505 ± .0015 (24.0)	.1833 ± .0014	.8203	.1504 ± .0011
142	BA (SFO)	.8173 (23.5)	.1515 ± .0015 (23.5)	.1845 ± .0018	.8167	.1507 ± .0015
143	BA (SFO)	.7807 (21.0)	.1439 ± .0015 (21.0)	.1842 ± .0014	.7768	.1431 ± .0011
144	TWA (MCI)	.8078 (22.0)	.1481 ± .0016 (22.0)	.1837 ± .0012	.8042	.1477 ± .0010
145	TWA (LGA)	.8053 (23.0)	.1489 ± .0016 (23.0)	.1835 ± .0019	.8040	.1475 ± .0015
146	BA (CDG)	.7847 (22.0)	.1438 ± .0015 (22.0)	.1833 ± .0014	.7818	.1433 ± .0011
147	BA (MIA)	.7991 (22.0)	.1465 ± .0016 (22.0)	.1830 ± .0014	.7966	.1458 ± .0011
148	TWA (STL)	.8023 (23.5)	.1468 ± .0015 (23.5)	.1832 ± .0011	.8019	.1469 ± .0009
149	TWA (DCA)	.8016 (23.5)	.1467 ± .0016 (23.5)	.1830 ± .0015	.8010	.1466 ± .0012
150	TWA (JFK)	.8048 (23.5)	.1478 ± .0016 (23.5)	.1834 ± .0019	.8043	.1475 ± .0015

Table III. Continued

Fuel ID number	Airline (airport)	ρ, g/cm^3 (T, °C)	μ, 1/cm (T, °C)	μ/ρ, cm^2/g	ρ_{24}, g/cm^3	μ_{24}, 1/cm
151	BA (HAM)	0.7878 (22.0)	0.1439 ± 0.0015 (22.0)	0.1832 ± 0.0015	0.7849	0.1438 ± 0.0012
152	BA (KHI)	.7805 (21.5)	.1422 ± .0015 (21.5)	.1834 ± .0019	.7773	.1426 ± .0015
153	BA (HEL)	.7873 (23.5)	.1455 ± .0015 (23.5)	.1839 ± .0019	.7868	.1447 ± .0015
154	BA (HAM)	.7900 (20.0)	.1445 ± .0015 (20.0)	.1830 ± .0013	.7845	.1436 ± .0010
155	BA (AKL)	.7875 (23.5)	.1443 ± .0015 (23.5)	.1835 ± .0014	.7870	.1444 ± .0011
156	BA (HKG)	.7830 (24.0)	.1448 ± .0015 (24.0)	.1844 ± .0012	.7829	.1444 ± .0009
157	BA (MUC)	.7838 (24.0)	.1441 ± .0015 (24.0)	.1834 ± .0013	.7839	.1438 ± .0010
158	SR (MBA)	.7827 (20.0)	.1454 ± .0015 (20.0)	.1849 ± .0017	.7775	.1438 ± .0013
159	KLM (AMS)	.7902 (23.0)	.1455 ± .0015 (23.0)	.1842 ± .0022	.7891	.1454 ± .0017
160	AA (SJU)	.7933 (21.0)	.1464 ± .0015 (21.0)	.1845 ± .0014	.7890	.1456 ± .0011
161	AA (IAD)	.8054 (23.5)	.1475 ± .0016 (23.5)	.1830 ± .0012	.8047	.1473 ± .0010
162	BA (KUL)	.7927 (22.0)	.1459 ± .0015 (22.0)	.1847 ± .0015	.7899	.1459 ± .0012
163	FM (MEM)	.8065 (22.0)	.1476 ± .0016 (22.0)	.1835 ± .0017	.8042	.1476 ± .0014
164	BA (DUS)	.8008 (23.5)	.1474 ± .0015 (23.5)	.1843 ± .0018	.8005	.1475 ± .0014
165	BA (BOM)	.7894 (22.0)	.1456 ± .0015 (22.0)	.1847 ± .0014	.7866	.1453 ± .0011
166	BA (BDA)	.8091 (22.0)	.1496 ± .0016 (22.0)	.1847 ± .0014	.8064	.1489 ± .0011
167	SA (JNB)	.7809 (24.0)	.1426 ± .0015 (24.0)	.1833 ± .0019	.7808	.1431 ± .0015
168	BA (DUB)	.7933 (22.0)	.1459 ± .0015 (22.0)	.1839 ± .0013	.7903	.1453 ± .0010
169	BA (VIE)	.7934 (22.0)	.1470 ± .0015 (22.0)	.1845 ± .0016	.7906	.1459 ± .0013
170	QF (MEL)	.8015 (24.0)	.1473 ± .0015 (24.0)	.1840 ± .0014	.8017	.1475 ± .0011
171	QF (PER)	.7848 (24.0)	.1457 ± .0015 (24.0)	.1854 ± .0014	.7847	.1455 ± .0011
172	QF (SYD)	.7837 (24.0)	.1441 ± .0015 (24.0)	.1832 ± .0015	.7837	.1436 ± .0012
173	QF (ADL)	.7792 (24.0)	.1441 ± .0015 (24.0)	.1847 ± .0014	.7791	.1439 ± .0011
174	QF (BNE)	.7776 (24.0)	.1441 ± .0015 (24.0)	.1847 ± .0016	.7774	.1436 ± .0012
175	BA (LHR)	.7863 (24.0)	.1445 ± .0015 (24.0)	.1843 ± .0016	.7861	.1449 ± .0013

Table III. Continued

Fuel ID number	Airline (airport)	ρ, g/cm^3 (T, °C)	μ, 1/cm (T, °C)	μ/ρ, cm^2/g	ρ_{24}, g/cm^3	μ_{24}, 1/cm
176	BA (ARN)	0.7906 (23.0)	0.1445 ± 0.0015 (23.0)	0.1832 ± 0.0015	0.7891	0.1446 ± 0.0012
177	AA (PHX)	.8187 (23.0)	.1504 ± .0016 (23.0)	.1834 ± .0014	.8173	.1499 ± .0011
178	BA (ARN)	.7940 (23.0)	.1466 ± .0015 (23.0)	.1843 ± .0014	.7928	.1461 ± .0011
179	SV (RUH)	.7810 (23.0)	.1437 ± .0015 (23.0)	.1843 ± .0015	.7796	.1437 ± .0012
180	SV (DAH)	.7795 (23.0)	.1440 ± .0015 (23.0)	.1838 ± .0017	.7781	.1430 ± .0013
181	SV (JED)	.7791 (23.0)	.1440 ± .0015 (23.0)	.1852 ± .0015	.7776	.1440 ± .0012
182	AF (NRT)	.7974 (22.5)	.1465 ± .0016 (22.5)	.1841 ± .0014	.7955	.1465 ± .0011
183	AF (TLS)	.7897 (22.5)	.1465 ± .0015 (22.5)	.1852 ± .0014	.7878	.1459 ± .0011
184	AF (GIG)	.7883 (22.5)	.1441 ± .0015 (22.5)	.1836 ± .0016	.7862	.1443 ± .0013
185	AF (NCE)	.7839 (22.5)	.1436 ± .0015 (22.5)	.1841 ± .0017	.7818	.1439 ± .0013
186	AF (FCO)	.7834 (24.0)	.1443 ± .0015 (24.0)	.1837 ± .0020	.7834	.1439 ± .0016
187	AF (LIN)	.7875 (23.0)	.1458 ± .0015 (23.0)	.1851 ± .0018	.7864	.1456 ± .0014
188	AF (TXL)	.7843 (23.0)	.1448 ± .0015 (23.0)	.1854 ± .0016	.7830	.1452 ± .0013
189	AF (BUE)	.7870 (23.0)	.1435 ± .0015 (23.0)	.1842 ± .0023	.7858	.1447 ± .0018
190	AF (ATH)	.7902 (22.5)	.1447 ± .0015 (22.5)	.1838 ± .0015	.7881	.1449 ± .0012
191	AF (ORY)	.7838 (23.0)	.1446 ± .0015 (23.0)	.1841 ± .0015	.7826	.1441 ± .0012
192	AF (LIS)	.7965 (23.0)	.1475 ± .0016 (23.0)	.1851 ± .0013	.7952	.1472 ± .0010
193	AF (CAI)	.7878 (23.0)	.1459 ± .0015 (23.0)	.1842 ± .0017	.7865	.1449 ± .0013
194	AF (MAD)	.8036 (23.0)	.1473 ± .0015 (23.0)	.1839 ± .0015	.8022	.1475 ± .0012
195	AF (CAY)	.8092 (22.5)	.1488 ± .0016 (22.5)	.1845 ± .0015	.8074	.1490 ± .0012
196	AF (OSA)	.7846 (24.0)	.1448 ± .0015 (24.0)	.1847 ± .0016	.7847	.1449 ± .0013
197	AF (MEX)	.7891 (23.0)	.1468 ± .0015 (23.0)	.1849 ± .0018	.7879	.1457 ± .0014
198	AF (CCS)	.7925 (23.0)	.1462 ± .0015 (23.0)	.1853 ± .0016	.7912	.1466 ± .0013
199	AF (PEK)	.7818 (23.0)	.1441 ± .0015 (23.0)	.1847 ± .0015	.7806	.1442 ± .0012
200	AF (SVO)	.7826 (23.0)	.1441 ± .0015 (23.0)	.1849 ± .0016	.7812	.1444 ± .0012

Table III. Continued

Fuel ID number	Airline (airport)	ρ, g/cm^3 (T, °C)	μ, 1/cm (T, °C)	μ/ρ, cm^2/g	ρ_{24}, g/cm^3	μ_{24}, 1/cm
201	BA (LGW)	0.7927 (23.5)	0.1473 ± 0.0015 (23.5)	0.1851 ± 0.0016	0.7919	0.1466 ± 0.0013
202	AC (YYZ)	.7963 (23.5)	.1474 ± .0015 (23.5)	.1847 ± .0014	.7957	.1470 ± .0011
203	TWA (MCI)	.8054 (23.5)	.1472 ± .0016 (23.5)	.1836 ± .0024	.8046	.1477 ± .0019
204	TWA (STL)	.8034 (23.5)	.1477 ± .0016 (23.5)	.1840 ± .0014	.8026	.1477 ± .0011
205	BA (DUS)	.8020 (23.5)	.1488 ± .0016 (23.5)	.1845 ± .0018	.8011	.1478 ± .0014
206	BA (MIA)	.7912 (23.0)	.1468 ± .0015 (23.0)	.1852 ± .0014	.7901	.1463 ± .0011
207	BA (TLV)	.7956 (23.0)	.1476 ± .0016 (23.0)	.1856 ± .0014	.7944	.1474 ± .0011
208	BA (CPH)	.7956 (23.0)	.1462 ± .0016 (23.0)	.1837 ± .0014	.7941	.1459 ± .0011
209	BA (AKL)	.7891 (24.0)	.1455 ± .0015 (24.0)	.1842 ± .0014	.7892	.1454 ± .0011
210	TWA (JFK)	.8059 (24.0)	.1490 ± .0016 (24.0)	.1843 ± .0015	.8059	.1485 ± .0012
211	TWA (LGA)	.8063 (24.0)	.1492 ± .0016 (24.0)	.1836 ± .0023	.8063	.1480 ± .0019
212	BA (BDA)	.8020 (24.0)	.1460 ± .0015 (24.0)	.1831 ± .0018	.8020	.1468 ± .0014
213	AC (YHZ)	.7836 (23.5)	.1435 ± .0015 (23.5)	.1837 ± .0015	.7827	.1438 ± .0012
214	BA (VIE)	.7853 (23.5)	.1441 ± .0015 (23.5)	.1832 ± .0014	.7846	.1437 ± .0011
215	BA (HEL)	.7879 (23.5)	.1454 ± .0015 (23.5)	.1839 ± .0015	.7871	.1447 ± .0012
216	AA (PHX)	.8116 (23.5)	.1484 ± .0016 (23.5)	.1832 ± .0014	.8109	.1486 ± .0011
217	BA (IST)	.7789 (25.0)	.1442 ± .0015 (25.0)	.1855 ± .0017	.7799	.1447 ± .0013
218	BA (FBU)	.7974 (23.5)	.1479 ± .0016 (23.5)	.1855 ± .0012	.7966	.1478 ± .0010
219	BA (KHI)	.7843 (25.0)	.1452 ± .0015 (25.0)	.1856 ± .0018	.7849	.1457 ± .0014
220	BA (MUC)	.7904 (24.0)	.1466 ± .0015 (24.0)	.1852 ± .0014	.7903	.1464 ± .0011
221	BA (SFO)	.8132 (24.0)	.1496 ± .0016 (24.0)	.1833 ± .0016	.8133	.1491 ± .0013
222	BA (LGW)	.7926 (23.5)	.1464 ± .0015 (23.5)	.1842 ± .0014	7919	.1459 ± .0011
223	AA (SJU)	.8082 (23.5)	.1487 ± .0016 (23.5)	.1838 ± .0014	.8075	.1484 ± .0011
224	AS (SEA)	.8129 (24.0)	.1482 ± .0016 (24.0)	.1833 ± .0017	.8130	.1490 ± .0014
225	KLM (AMS)	.7888 (24.0)	.1438 ± .0015 (24.0)	.1845 ± .0026	.7888	.1455 ± .0021

Table III. Continued

Fuel ID number	Airline (airport)	ρ, g/cm^3 (T, °C)	μ, 1/cm (T, °C)	μ/ρ, cm^2/g	ρ_{24}, g/cm^3	μ_{24}, 1/cm
226	SR (ZRH)	0.7917 (24.0)	0.1468 ± 0.0015 (24.0)	0.1850 ± 0.0015	0.7916	0.1464 ± 0.0012
227	TWA (DCA)	.8042 (24.0)	.1472 ± .0016 (24.0)	.1846 ± .0031	.8042	.1485 ± .0025
228	BA (NBO)	.7832 (23.0)	.1447 ± .0015 (23.0)	.1842 ± .0015	.7819	.1440 ± .0012
229	SR (MBA)	.7829 (23.0)	.1437 ± .0015 (23.0)	.1838 ± .0014	.7815	.1436 ± .0011
230	SR (GVA)	.7887 (23.0)	.1464 ± .0015 (23.0)	.1838 ± .0024	.7873	.1447 ± .0019
231	SA (JNB)	.7860 (23.0)	.1453 ± .0015 (23.0)	.1849 ± .0014	.7847	.1451 ± .0011
232	SA (JNB)	.7895 (23.5)	.1446 ± .0015 (23.5)	.1838 ± .0015	.7887	.1450 ± .0012
233	AC (YMX)	.7987 (23.5)	.1478 ± .0016 (23.5)	.1847 ± .0014	.7980	.1474 ± .0011
234	AS (SEA)	.8087 (23.5)	.1482 ± .0016 (23.5)	.1834 ± .0014	.8081	.1482 ± .0011
235	AC (YUL)	.7916 (23.5)	.1461 ± .0015 (23.5)	.1844 ± .0014	.7910	.1459 ± .0011
236	BA (DUB)	.7956 (23.0)	.1458 ± .0015 (23.0)	.1833 ± .0013	.7944	.1456 ± .0010
237	BA (BKK)	.7878 (23.5)	.1450 ± .0015 (23.5)	.1835 ± .0015	.7872	.1445 ± .0012
238	BA (HAM)	.7970 (24.0)	.1465 ± .0015 (24.0)	.1852 ± .0020	.7973	.1477 ± .0016
239	BA (ARN)	.7955 (24.0)	.1453 ± .0015 (24.0)	.1842 ± .0021	.7954	.1465 ± .0017
240	BA (CDG)	.7871 (24.0)	.1453 ± .0015 (24.0)	.1846 ± .0020	.7871	.1453 ± .0016
241	SV (JED)	.7815 (23.5)	.1434 ± .0015 (23.5)	.1841 ± .0015	.7808	.1437 ± .0012
242	SV (DAH)	.7796 (23.5)	.1447 ± .0015 (23.5)	.1849 ± .0016	.7790	.1440 ± .0012
243	SV (RUH)	.7828 (23.5)	.1452 ± .0015 (23.5)	.1853 ± .0013	.7820	.1449 ± .0010
244	BA (KUL)	.7877 (23.5)	.1455 ± .0015 (23.5)	.1849 ± .0014	.7869	.1455 ± .0011
245	QF (SYD)	.7881 (24.0)	.1465 ± .0015 (24.0)	.1847 ± .0018	.7882	.1456 ± .0014
246	QF (ADL)	.7784 (24.0)	.1440 ± .0015 (24.0)	.1854 ± .0014	.7786	.1444 ± .0011
247	QF (BNE)	.7819 (23.5)	.1447 ± .0015 (23.5)	1853 ± .0014	7821	.1449 ± .0011
248	QF (PER)	.7831 (24.0)	.1444 ± .0015 (24.0)	.1840 ± .0014	.7830	.1441 ± .0011
249	QF (MEL)	.7861 (24.0)	.1451 ± .0015 (24.0)	.1849 ± .0014	.7860	.1453 ± .0011
250	SA (JNB)	.7897 (23.5)	.1465 ± .0015 (23.5)	.1855 ± .0011	.7891	.1464 ± .0009

Table III. Concluded

Fuel ID number	Airline (airport)	ρ, g/cm^3 (T, °C)	μ, 1/cm (T, °C)	μ/ρ, cm^2/g	ρ_{24}, g/cm^3	μ_{24}, 1/cm
251	BA (BOM)	0.7843 (23.0)	0.1449 ± 0.0015 (23.0)	0.1847 ± 0.0013	0.7831	0.1446 ± 0.0010
252	AF (SVO)	.7817 (22.0)	.1442 ± .0015 (22.0)	.1847 ± .0014	.7791	.1439 ± .0011
253	AF (PEK)	.7828 (21.0)	.1446 ± .0015 (21.0)	.1846 ± .0014	.7788	.1438 ± .0011
254	AF (TXL)	.7939 (21.0)	.1461 ± .0015 (21.0)	.1843 ± .0014	.7900	.1456 ± .0011
255	AF (GIG)	.7820 (21.0)	.1441 ± .0015 (21.0)	.1839 ± .0014	.7779	.1431 ± .0011
256	AF (MAD)	.8009 (21.0)	.1470 ± .0015 (21.0)	.1833 ± .0014	.7968	.1461 ± .0011
257	AF (CCS)	.8099 (21.0)	.1499 ± .0015 (21.0)	.1853 ± .0014	.8058	.1493 ± .0011
258	AF (FCO)	.7920 (21.0)	.1466 ± .0015 (21.0)	.1851 ± .0013	.7878	.1458 ± .0010
259	AF (CAY)	.8187 (22.0)	.1498 ± .0015 (22.0)	.1832 ± .0010	.8131	.1490 ± .0008
260	AF (NCE)	.7996 (21.0)	.1469 ± .0015 (21.0)	.1840 ± .0014	.7954	.1464 ± .0011
261	AF (ORY)	.7856 (21.0)	.1454 ± .0015 (21.0)	.1839 ± .0018	.7814	.1437 ± .0014
262	AF (LIN)	.7880 (21.0)	.1457 ± .0015 (21.0)	.1848 ± .0014	.7838	.1448 ± .0011
263	AF (MEX)	.7904 (21.0)	.1464 ± .0015 (21.0)	.1845 ± .0015	.7862	.1451 ± .0012
264	AF (OSA)	.7822 (21.5)	.1442 ± .0015 (21.5)	.1838 ± .0015	.7789	.1432 ± .0012
265	AF (CAI)	.7890 (21.5)	.1437 ± .0015 (21.5)	.1831 ± .0017	.7855	.1438 ± .0013
266	AF (ATH)	.7899 (21.5)	.1446 ± .0015 (21.5)	.1837 ± .0015	.7866	.1445 ± .0012
267	AF (NRT)	.7860 (22.0)	.1449 ± .0015 (22.0)	.1847 ± .0014	.7834	.1447 ± .0011
268	AF (LIS)	.8002 (22.0)	.1482 ± .0015 (22.0)	.1835 ± .0022	.7976	.1464 ± .0018
269	AF (TLS)	.7850 (22.0)	.1443 ± .0015 (22.0)	.1837 ± .0014	.7822	.1437 ± .0011
270	AF (BUE)	.7860 (22.0)	.1452 ± .0015 (22.0)	.1846 ± .0014	.7833	.1446 ± .0011

Table IV. Rate of Change of Density for Selected Fuel Samples

Number	Fuel ID number	Airline (airport)	$d\rho/dT$, g/cm^3 per 1°C
1	5	AC (YHZ)	−0.001900
2	6	TWA (JFK)	−.001400
3	20	AS (SEA)	−.001300
4	21	FT (BRU)	−.001800
5	26	BA (FBU)	−.001067
6	27	BA (HEL)	−.001400
7	28	BA (MUC)	−.001133
8	29	BA (CDG)	−.001067
9	30	BA (AKL)	−.001200
10	33	BA (BKK)	−.001467
11	36	BA (DEL)	−.001067
12	38	BA (HAM)	−.001467
13	40	AF (ATH)	−.001600
14	60	BA (LHR)	−.002000
15	65	TWA (LGA)	−.001250
16	66	TWA (JFK)	−.001000
17	69	BA (ARN)	−.001800
18	78	BA (IST)	−.001000
19	79	BA (BOM)	−.001200
20	88	AC (YUL)	−.001067
21	90	BA (DUB)	−.001400
22	91	AC (YYZ)	−.002000
23	92	BA (BDA)	−.002000
24	93	FM (MEM)	−.001000
25	96	TWA (STL)	−.001500
26	98	BA (HAM)	−.001000
27	105	AA (IAD)	−.001267
28	110	AF (NRT)	−.001300
29	113	AF (MAD)	−.001600
30	122	AF (FCO)	−.001200
31	133	QF (ADL)	−.001800
32	137	BA (FBU)	−.001400
33	144	TWA (MCI)	−.001850
34	145	TWA (LGA)	−.001200
35	149	TWA (DCA)	−.001133
36	153	BA (HEL)	−.001250
37	156	BA (HKG)	−.001325
38	157	BA (MUC)	−.001300
39	159	KLM (AMS)	−.001200
40	161	AA (IAD)	−.001200
41	163	FM (MEM)	−.001200
42	164	BA (DUS)	−.001133
43	221	BA (SFO)	−.001000

Table V. Correlation Between Sample Numbers and Fuel ID Numbers

(a) Region I (North America)

Airline (airport)	Sample number	Fuel ID number(s) for summer (June–Aug.)	Sample number	Fuel ID number(s) for fall (Sept.–Nov.)	Sample number	Fuel ID number(s) for winter (Dec.–Feb.)	Sample number	Fuel ID number(s) for spring (Mar.–May)
AA (BNA)	1	7	22	61, 62	43	136	64	
AA (PHX)	2	8	23	74	44		65	177, 216
AA (SJU)	3	223	24	14	45	84	66	160
AA (IAD)	4		25	15	46	105	67	161
AA (DFW)	5		26		47	128	68	
AC (YHZ)	6	5	27	58	48		69	213
AC (YMX)	7	9, 233	28		49	89	70	
AC (YUL)	8	10, 235	29		50	88	71	
AC (YYZ)	9	11	30		51	91	72	202
AS (SEA)	10	224, 234	31	20	52		73	
AS (ANC)	11		32	23	53	106	74	
BA (MIA)	12		33	22, 82	54	147	75	206
BA (BDA)	13		34		55	85, 92	76	166, 212
BA (SFO)	14	221	35		56	142, 143	77	
FM (MEM)	15		36	19	57	93	78	163
FT (LAX)	16		37	16	58	141	79	
TWA (MCI)	17	1	38		59	94, 144	80	203
TWA (JFK)	18	6	39	66	60	150	81	210
TWA (LGA)	19		40	13, 65	61	145	82	211
TWA (DCA)	20	227	41	17	62	95, 149	83	
TWA (STL)	21		42	18	63	96, 148	84	204

Table V. Continued

(b) Region II (Europe)

Airline (airport)	Sample number	Fuel ID number(s) for summer (June–Aug.)	Sample number	Fuel ID number(s) for fall (Sept.–Nov.)	Sample number	Fuel ID number(s) for winter (Dec.–Feb.)	Sample number	Fuel ID number(s) for spring (Mar.–May)
AF (ATH)	1		27	40	53	112, 266	79	190
AF (ORY)	2		28	41	54	120, 261	80	191
AF (TXL)	3		29	45	55	114, 254	81	188
AF (TLS)	4		30	46	56	117, 269	82	183
AF (FCO)	5		31	47	57	122, 258	83	186
AF (NCE)	6		32	48	58	121, 260	84	185
AF (LIS)	7		33	52	59	118, 268	85	192
AF (LIN)	8		34	53	60	109, 262	86	187
AF (SVO)	9		35	55	61	108, 252	87	200
AF (MAD)	10		36	64	62	113, 256	88	194
BA (CPH)	11		37	24, 73	63	140	89	208
BA (FBU)	12	218	38	26, 76	64	137	90	
BA (HEL)	13		39	27, 77	65	153	91	215
BA (MUC)	14	220	40	28, 70	66	157	92	
BA (CDG)	15	240	41	29, 67	67	146	93	
BA (DUB)	16	236	42	31	68	90	94	168
BA (DUS)	17		43	32, 81	69		95	164, 205
BA (VIE)	18		44	35, 80	70		96	169, 214
BA (HAM)	19	238	45	37, 38	71	97, 98, 99, 151, 154	97	
BA (LGW)	20	222	46	59	72	127	98	201
BA (LHR)	21		47	60	73	135	99	175
BA (ARN)	22	239	48	69	74		100	176, 178
FT (BRU)	23		49	21	75	134	101	
KLM (AMS)	24	225	50	12, 72	76		102	159
SR (ZRH)	25	2, 226	51		77	103	103	
SR (GVA)	26	3, 230	52		78	104	104	

Table V. Concluded

(c) Region III (All other areas)

Airline (airport)	Sample number	Fuel ID number(s) for summer (June–Aug.)	Sample number	Fuel ID number(s) for fall (Sept.–Nov.)	Sample number	Fuel ID number(s) for winter (Dec.–Feb.)	Sample number	Fuel ID number(s) for spring (Mar.–May)
AF (GIG)	1		30	42	59	111, 255	88	184
AF (CAI)	2		31	43	60	115, 265	89	193
AF (MEX)	3		32	44	61	124, 263	90	197
AF (NRT)	4		33	49	62	110, 267	91	182
AF (OSA)	5		34	50	63	119, 264	92	196
AF (CAY)	6		35	51	64	116, 259	93	195
AF (BUE)	7		36	54	65	123, 270	94	189
AF (CCS)	8		37	56	66	125, 257	95	198
AF (PEK)	9		38	63	67	107, 253	96	199
BA (TLV)	10		39	25, 75	68	138	97	207
BA (AKL)	11		40	30, 57	69	155	98	209
BA (BKK)	12	237	41	33	70	100	99	
BA (KHI)	13	219	42	34	71	86, 152	100	
BA (DEL)	14		43	36	72	87	101	
BA (KUL)	15	244	44	39	73	126	102	162
BA (HKG)	16		45	68, 83	74	156	103	
BA (IST)	17		46	71, 78	75	139	104	217
BA (BOM)	18	251	47	79	76	101	105	165
BA (NBO)	19	228	48		77		106	
QF (SYD)	20	245	49		78	129	107	172
QF (MEL)	21	249	50		79	130	108	170
QF (BNE)	22	247	51		80	131	109	174
QF (PER)	23	248	52		81	132	110	171
QF (ADL)	24	246	53		82	133	111	173
SA (JNB)	25	231, 232, 250	54		83		112	167
SR (MBA)	26	4, 229	55		84	102	113	158
SV (RUH)	27	243	56		85		114	179
SV (DAH)	28	242	57		86		115	180
SV (JED)	29	241	58		87		116	181

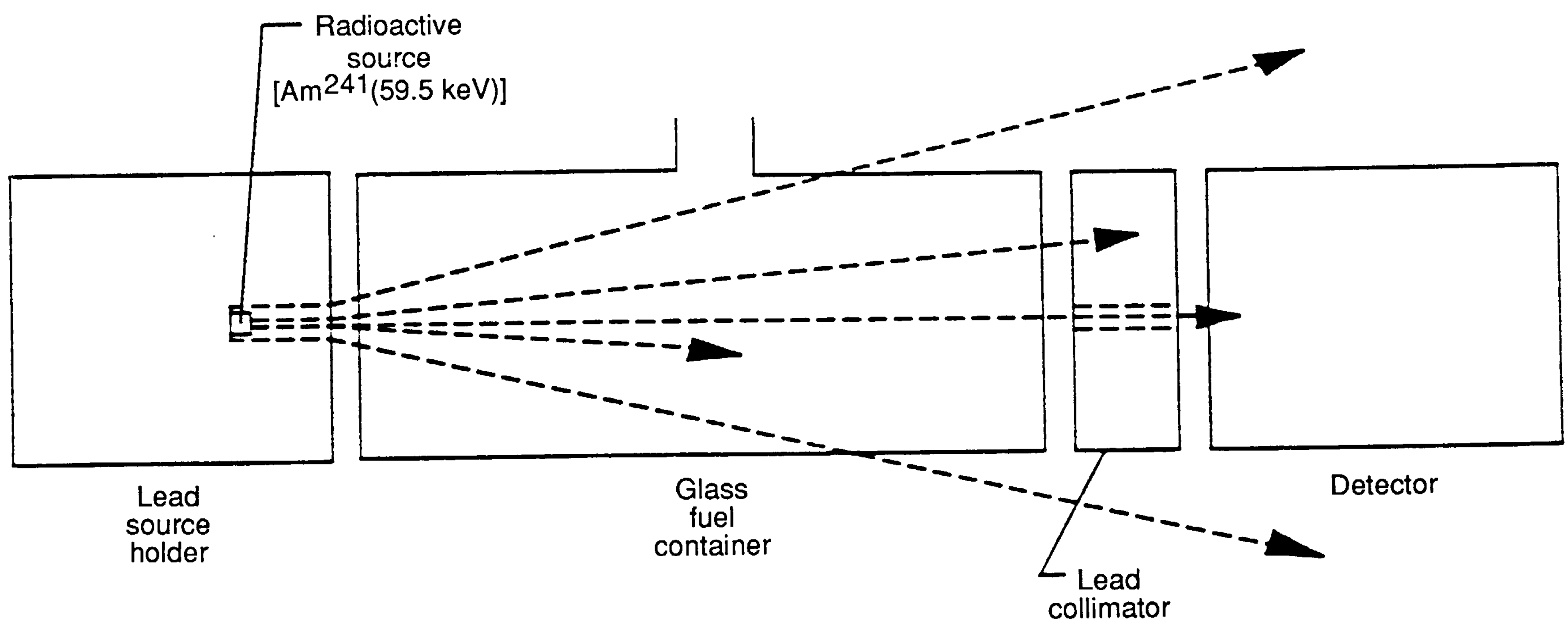


Figure 1. Source-detector arrangement.

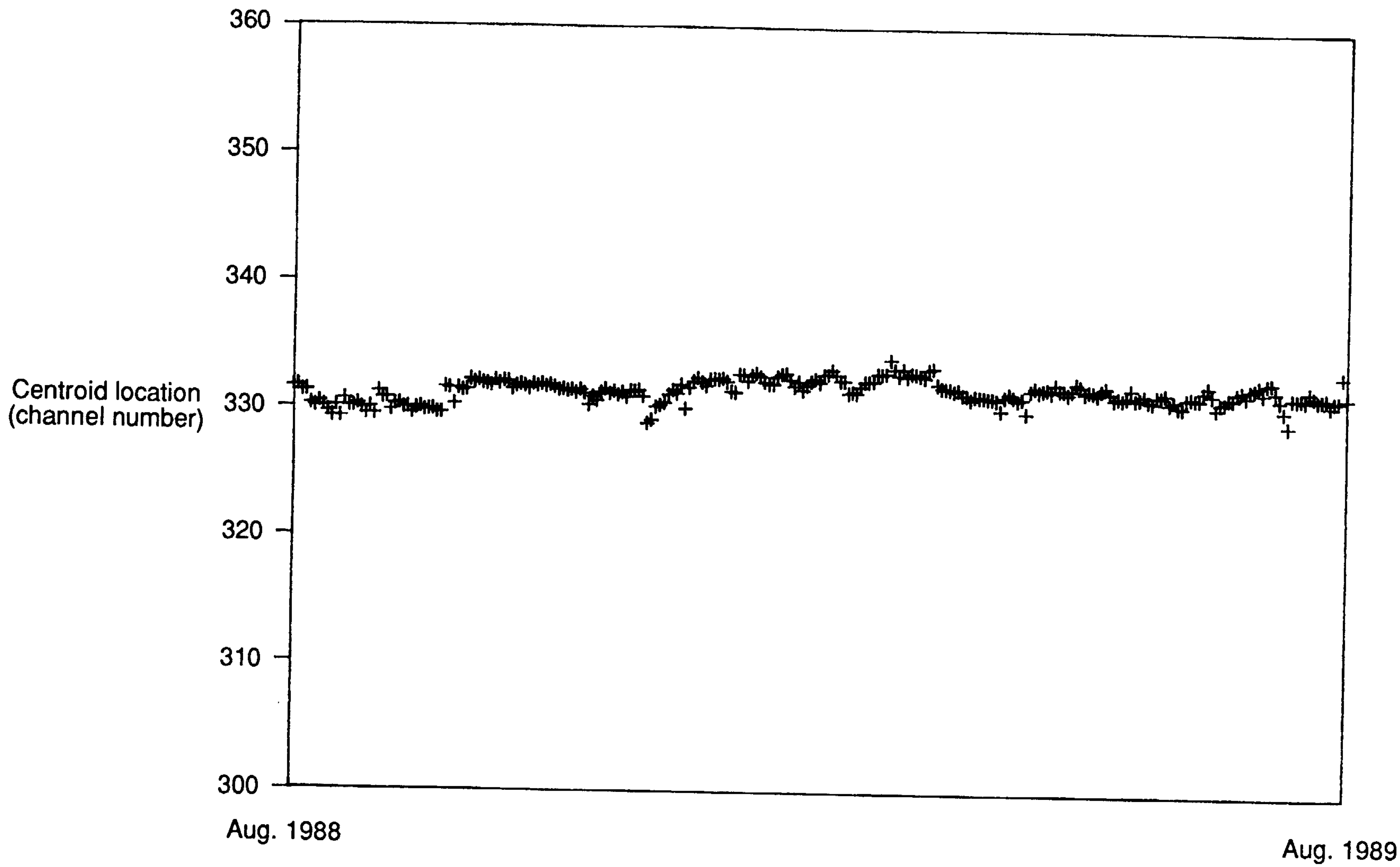


Figure 2. Experimental system stability test (location of air spectrum centroid).

Figure 3. Global distribution of airports sampled.

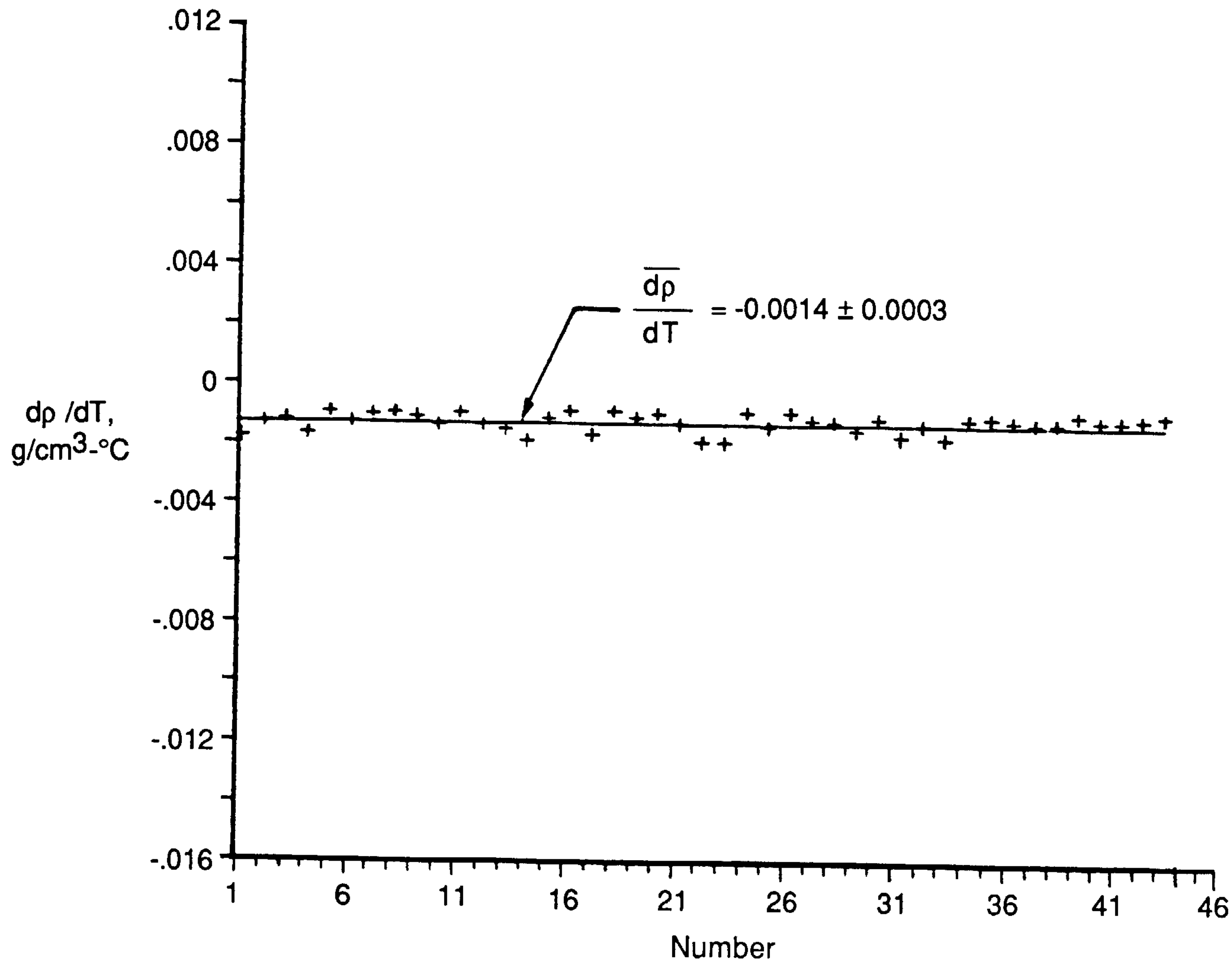


Figure 4. Rate of change of density for selected fuel samples. (See table IV.)

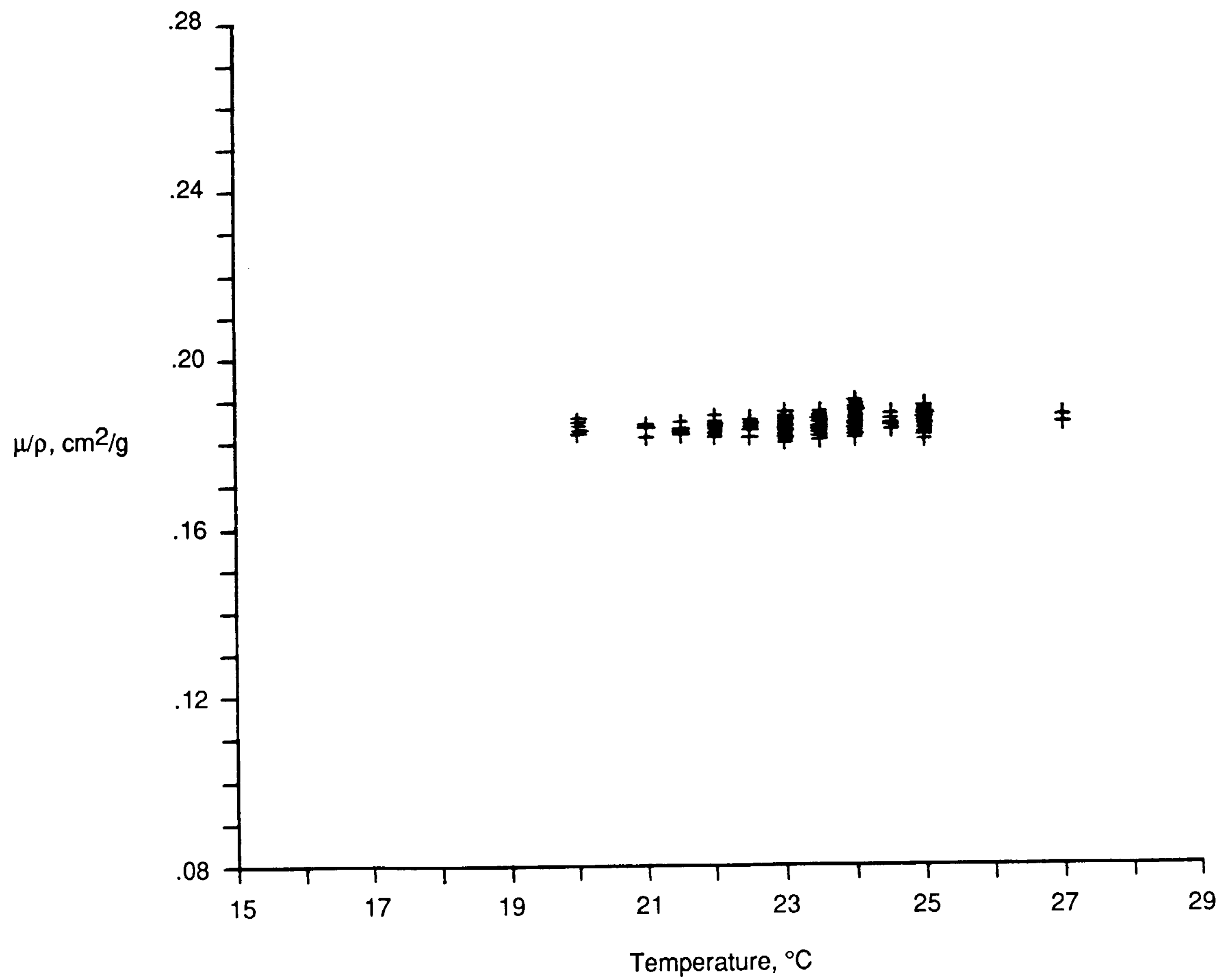
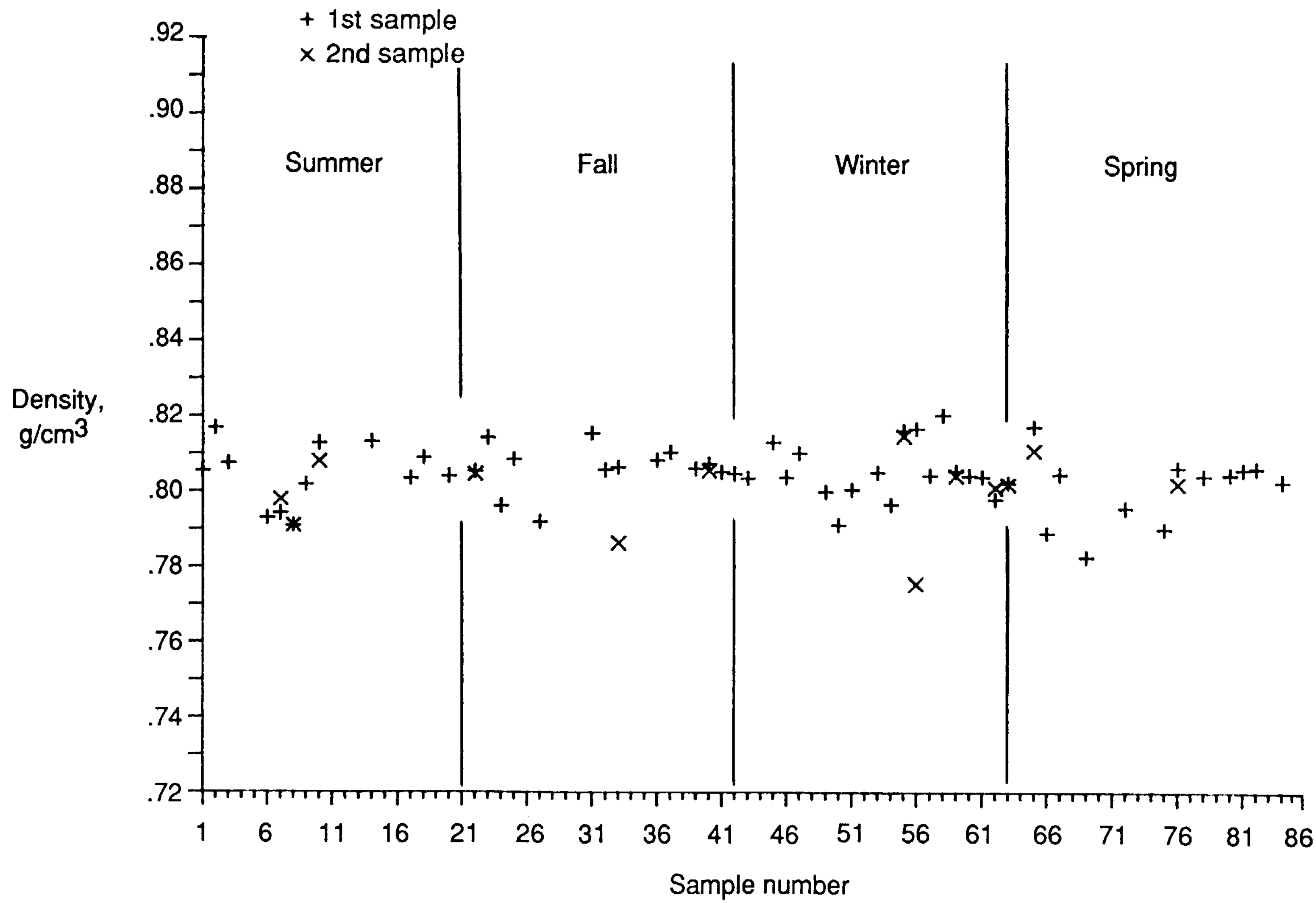
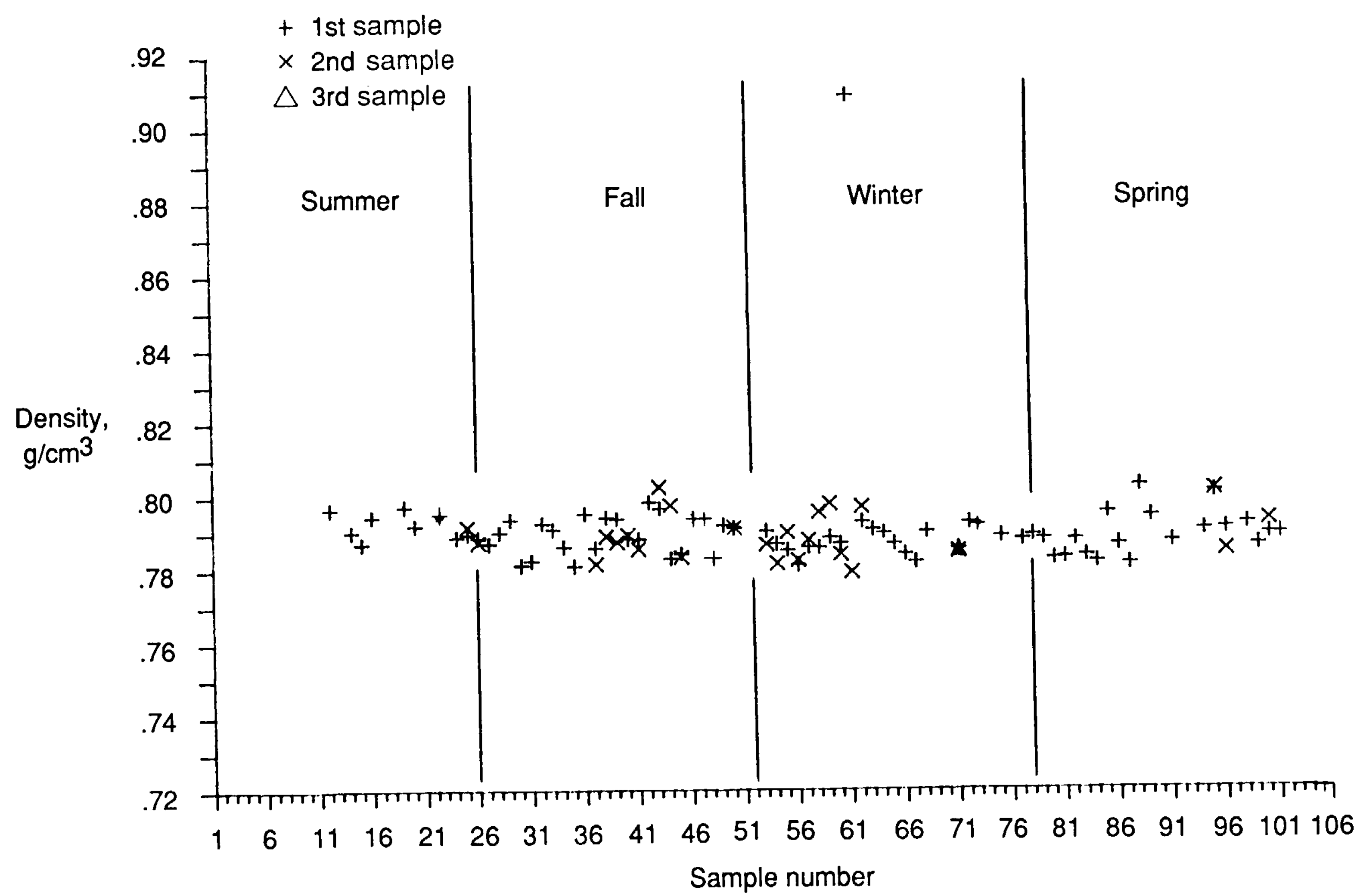


Figure 5. Comparison of μ/ρ values at different temperatures.



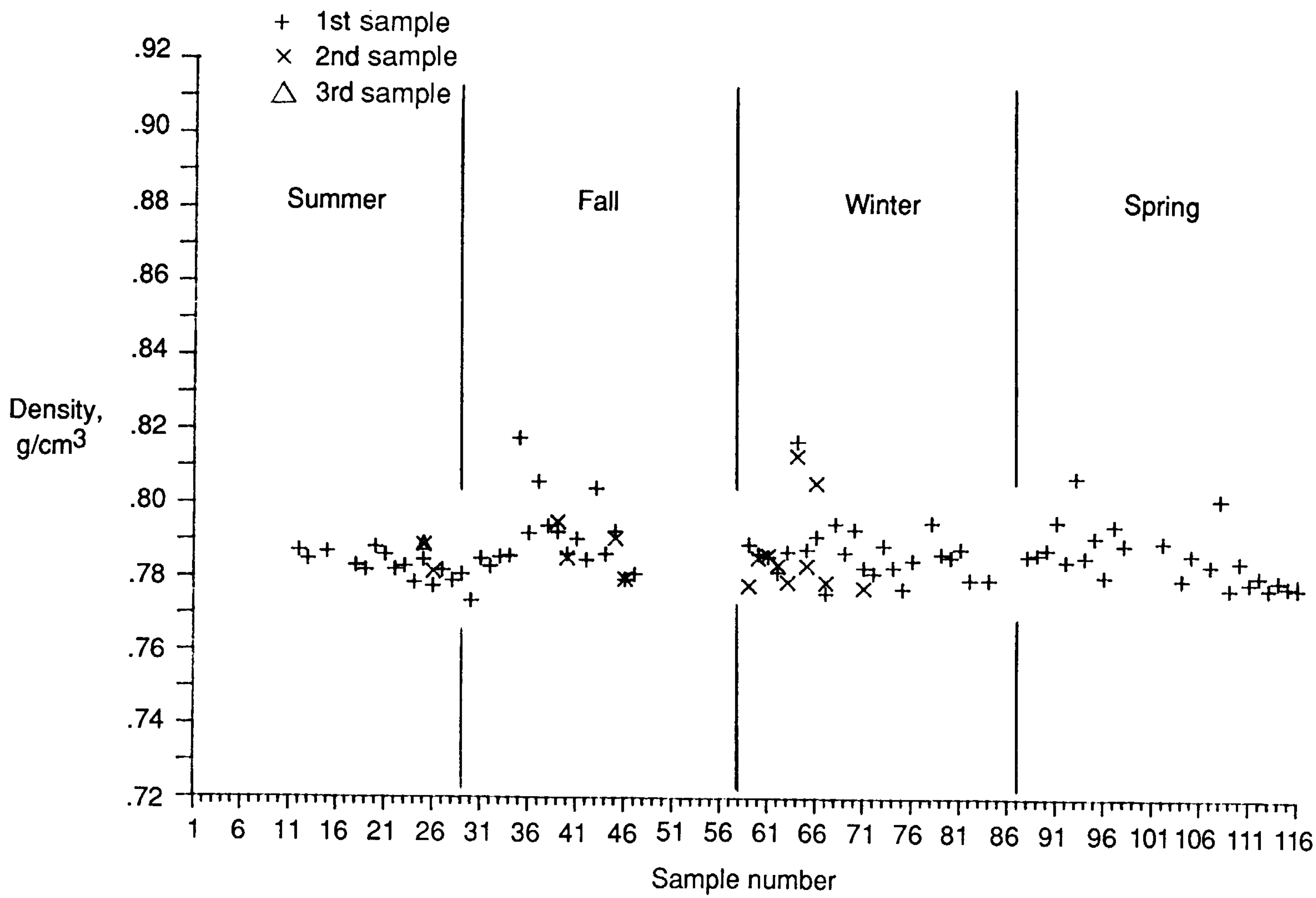
(a) Region I (North America).

Figure 6. Seasonal variation of fuel density. $T = 24°C$.



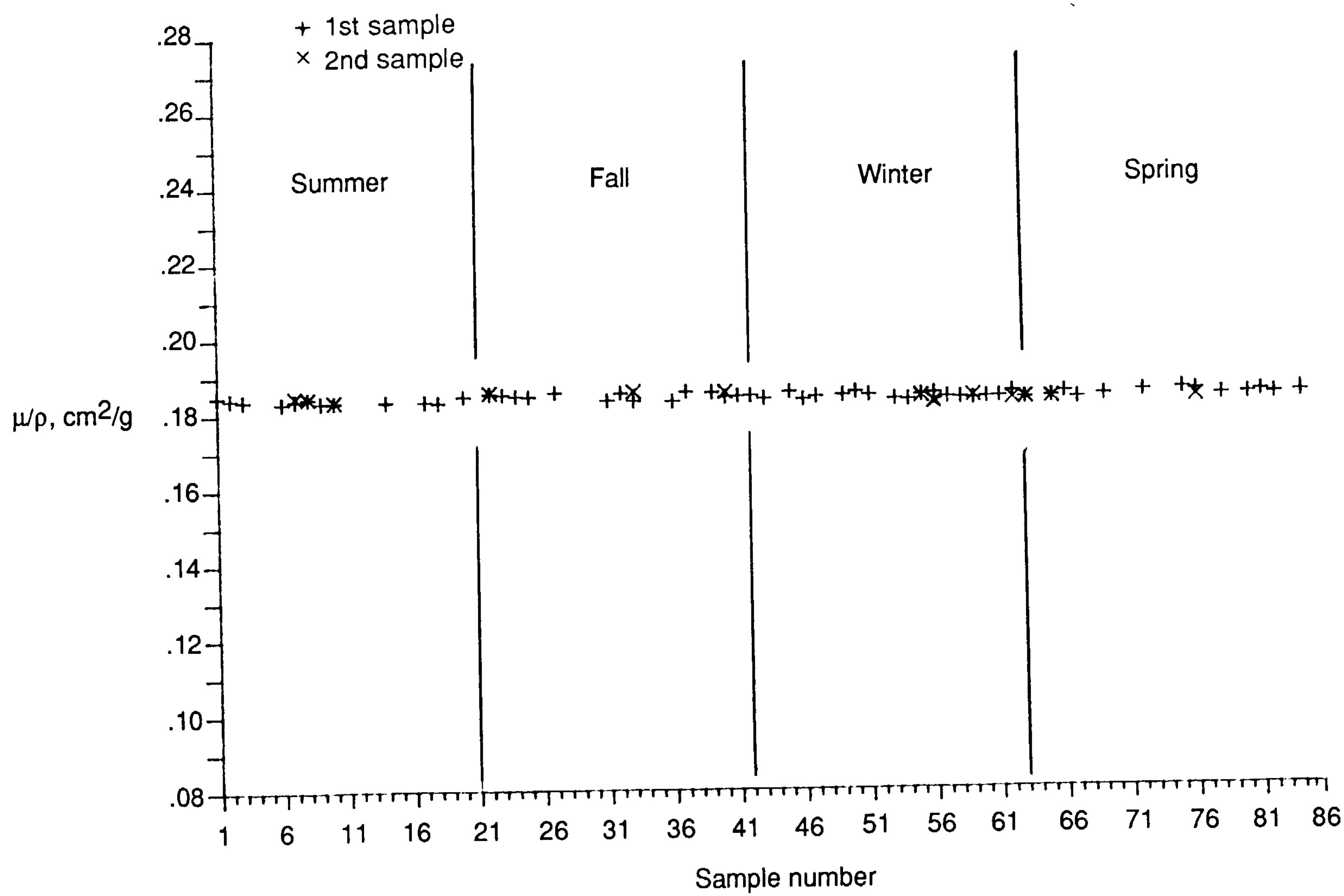
(b) Region II (Europe).

Figure 6. Continued.



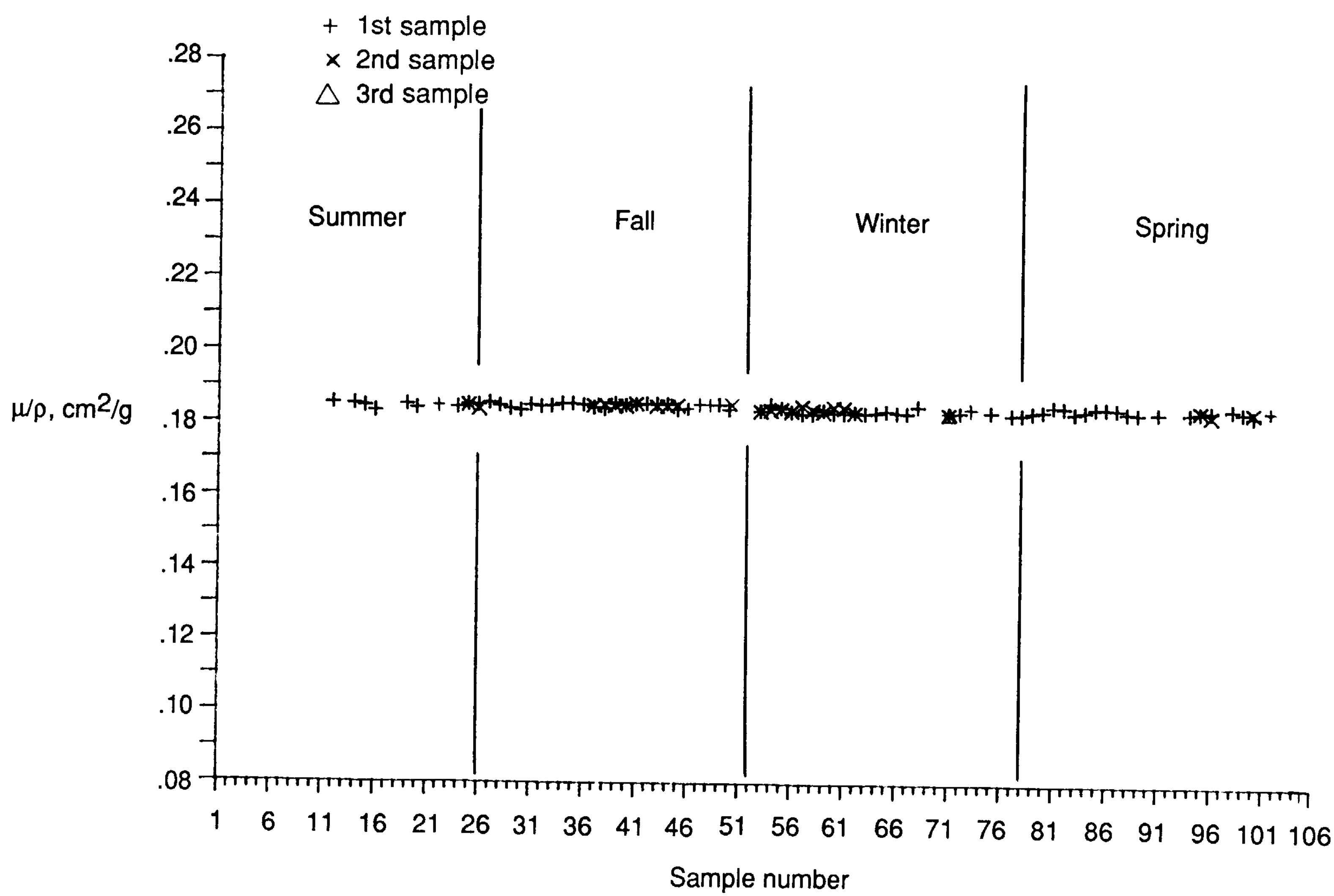
(c) Region III (all other areas).

Figure 6. Concluded.



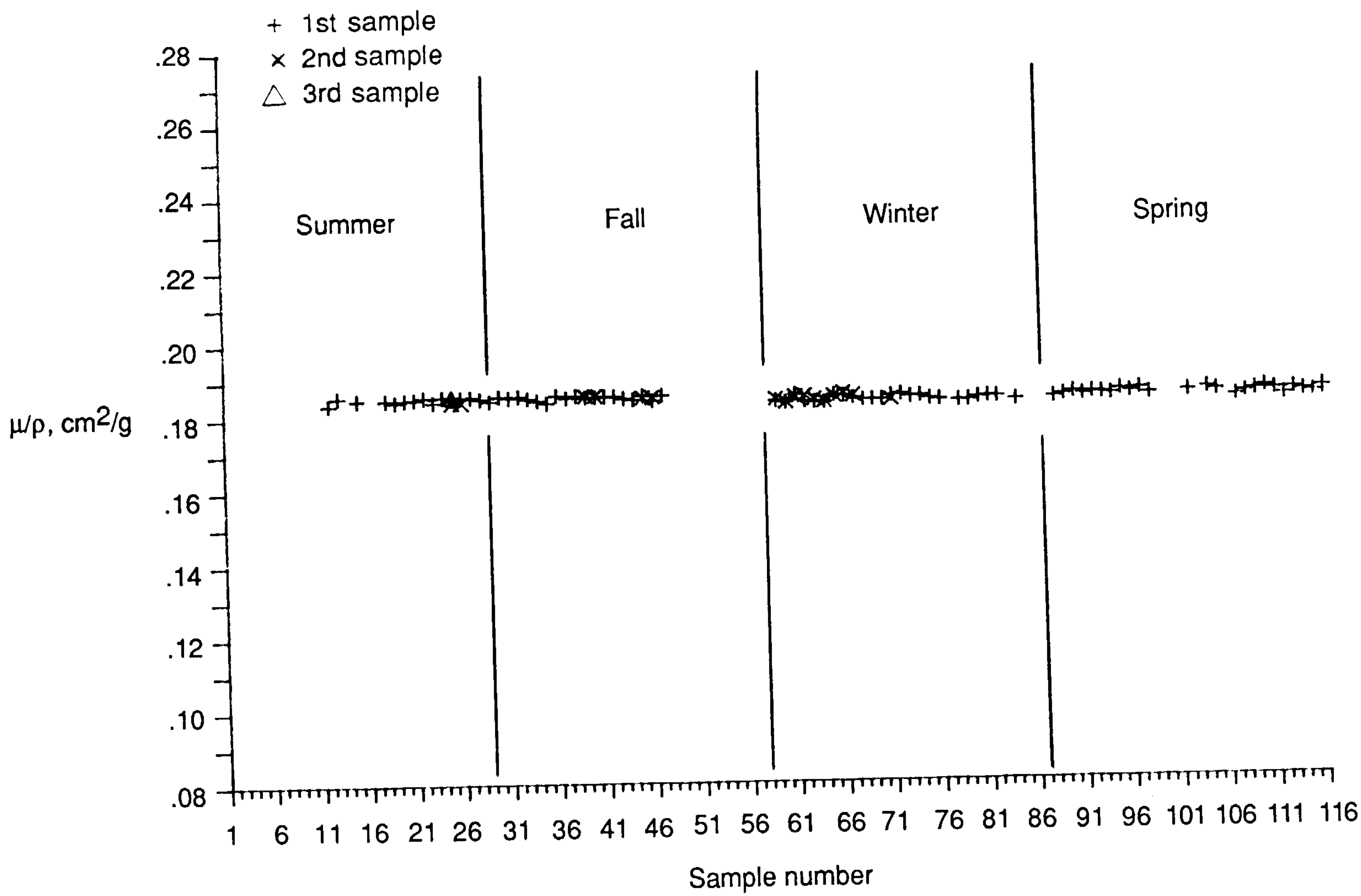
(a) Region I (North America).

Figure 7. Seasonal variation of mass attenuation coefficient.



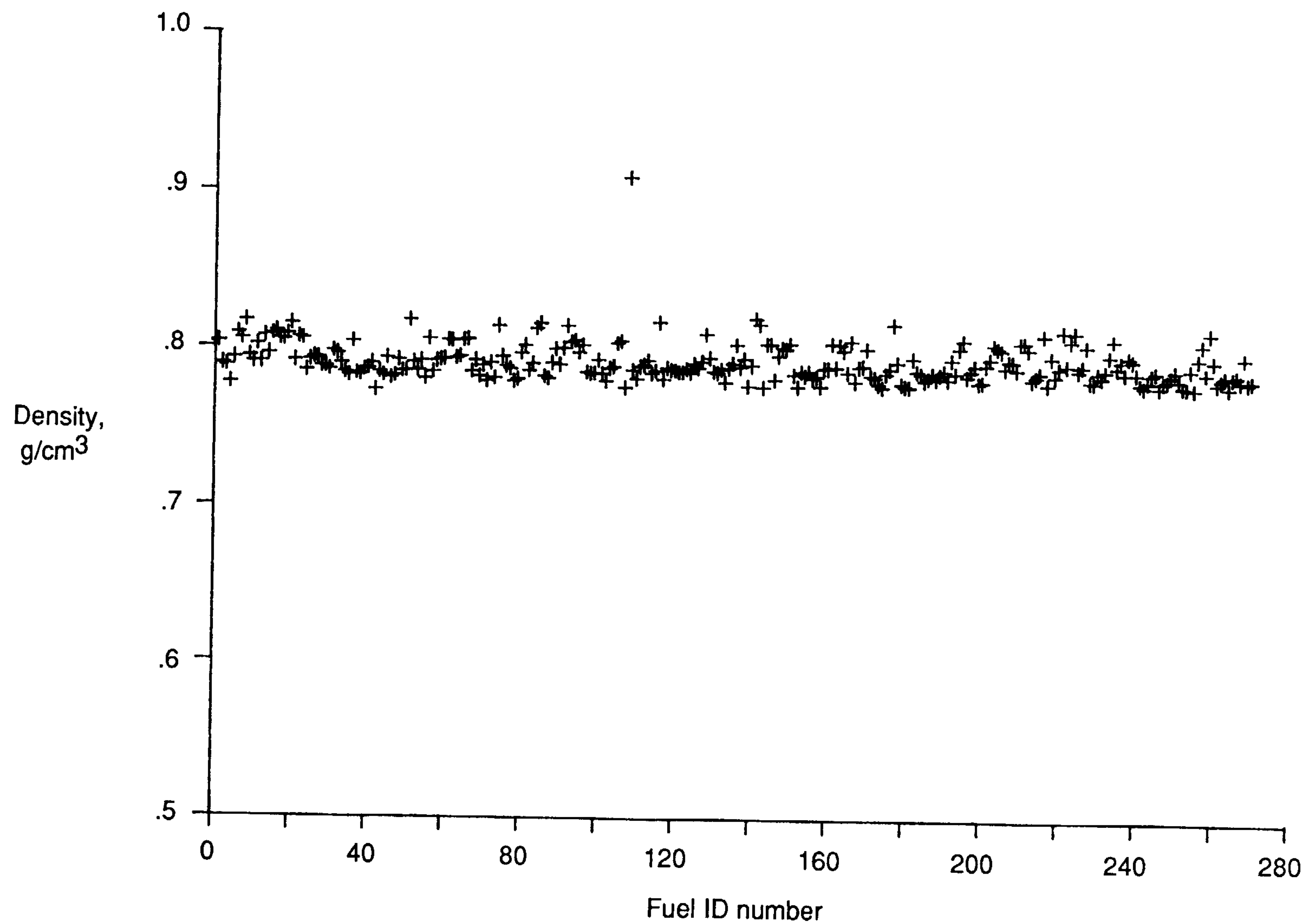
(b) Region II (Europe).

Figure 7. Continued.



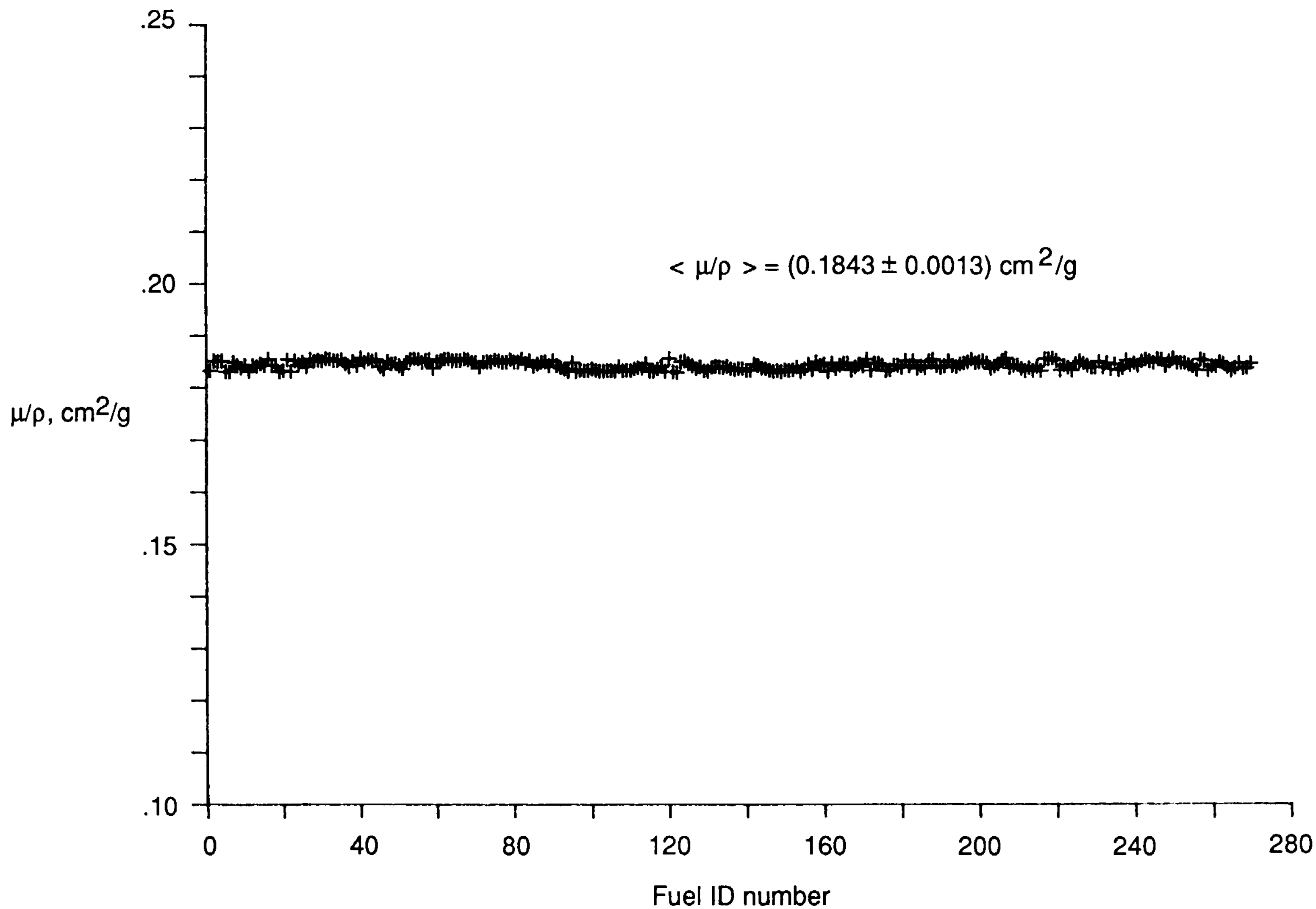
(c) Region III (all other areas).

Figure 7. Concluded.



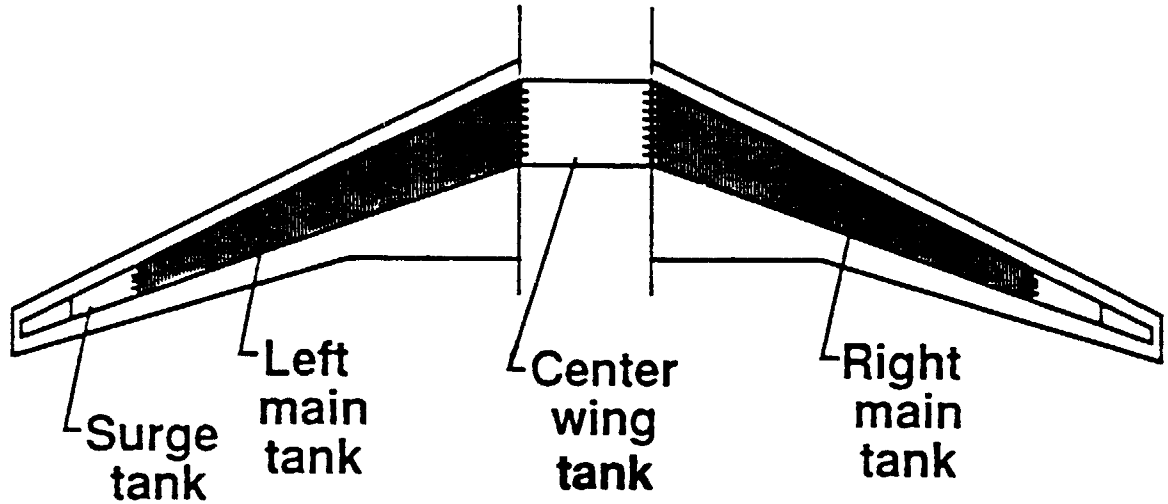
(a) Normalized density: $T = 24°C$.

Figure 8. Density and mass attenuation coefficient of aviation fuel samples.

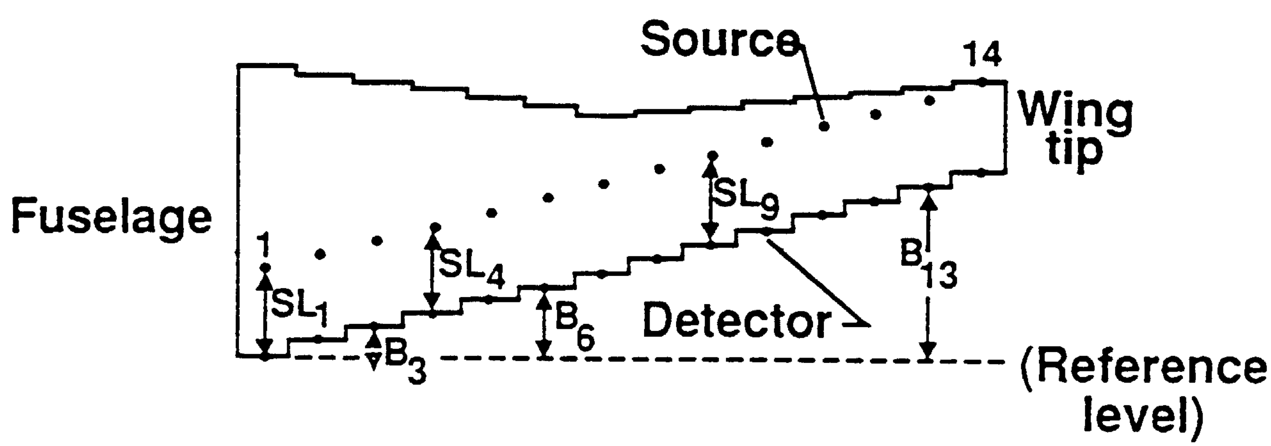


(b) Mass attenuation coefficient.

Figure 8. Concluded.



(a) Fuel tank arrangements in aircraft.



(b) Vertical cross section of wing tank in flight.

Figure 9. Locations of source-detector assemblies in wing tank in flight. Source-detector separation is held constant. Wing lifts up during flight through height with respect to reference level.

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16. Abstract

Gamma ray attenuation characteristics of AM^{241} were investigated in 270 aviation fuel samples (Jet A and Jet A-1) from 76 airports around the world as part of a year-long study to measure variability of aviation fuel properties as a function of season and geographical origin. All measurements were made at room temperature (20°C to 27°C). Fuel density was measured concurrently with linear attenuation coefficient to provide a measure of mass attenuation coefficient for the test samples. In 43 fuel samples, density and linear attenuation were measured at more than one room temperature, the result being mass attenuation coefficients at several temperatures. The results were found to be independent of the temperature at which linear attenuation and density were measured. Although individually density and linear attenuation vary considerably from airport to airport as well as from season to season, mass attenuation for all samples is constant at $0.1843 \pm 0.0013\ cm^2/g$. This constancy of mass attenuation for aviation fuels is significant since it indicates a fuel quantity gauging system based on low-energy gamma ray attenuation is viable throughout the world.

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