

**CRC Report No. AV-27-18**

**MEASUREMENT OF AVIATION FUEL  
PROPERTIES RELEVANT FOR THE  
ESTIMATION OF V/L RATIO  
PARAMETER CALCULATION**

**Final Report**

**January 2022**



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University of Dayton  
Research Institute

UDR-TR-2021-90

## **CRC Project No. AV-27-18: Measurement of Aviation Fuel Properties Relevant for the Estimation of V/L Ratio Parameter Calculation**

(Publically releasable version of UDRI Report: UDR-TR-2021-161)

### **Final Report**

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## BACKGROUND

The development of higher Mach jet aircraft in the 1950s, which began operating at higher altitudes with higher fuel temperatures and increased fuel flow requirements, created the need for more definitive design parameters between the aircraft fuel delivery system and the aircraft engine fuel system for these modern aircraft. Since then, aircraft engine fuel system design relies upon the derived fuel vapor-liquid ratio (V/L), as the design criterion for the condition of fuel at the aircraft/engine interface [AIR1326A]. As reported in numerous SAE International publications, i.e., AIR1326, ARP492, ARP4024, and ARP4028, the V/L ratio is used to determine the ability of a fuel pump to operate when presented with a fuel and gas (slugging flow), the minimum required total inlet pressure (net positive suction head) for fuel phase only, and the resistance to degradation due to pump failure (cavitation).

The V/L ratio parameter can be measured directly (method I) using an inline meter, e.g., capacitance meter, or indirectly via calculation from fluid properties (method II). The direct measurement of V/L using a meter is the preferred method of determination reported in AIR 1326 A, the ARP492C does not provide a preference for either method. While method I may provide a more accurate V/L parameter under the specific test/experimental conditions, the derived method (method II) can be used more generally for overall fuel system design. Therefore, both methods of determining the V/L parameter require adequate scrutiny.

The V/L computation estimates the amount of air and fuel vapor that come out of solution in a closed fuel line due to the change in pressure and temperature between two stations within the fuel system, e.g., from the fuel tank to the suction (inlet) of the fuel pump. The V/L computation outlined in AIR1326 requires both fluid property data, i.e., air solubility (S) or solubility coefficient (k) and fluid true vapor pressure (TVP), as well as system specific data, e.g., fuel temperature and pressure conditions at each station. Both AIR1326 and the CRC Aviation Fuels Handbook [CRC Report 663, 2013] provide some data on air solubility, and the CRC Aviation Fuels Handbook provides estimates of fuel vapor pressures. However, the origin of these property data appear to be from reports generated in the 1950's and more recent data sources (to include contemporary fuels) are of interest.

With this in mind, the Coordinating Research Council (CRC) initiated a project to generate relevant fuel property data, for a robust set of modern aviation turbine fuels, that could be used by the community to update the SAE documents dealing with V/L and gas solubility, as well as updating appropriate CRC and ASTM published properties for both petroleum and alternative fuel sources. The purpose of this program was not to evaluate the applicability of the derived V/L ratio for modern aviation fuels. The program objective, to measure relevant fuel property data, was achieved and the subsequent data are presented herein.

## EXPERIMENTAL

Our approach to providing a comprehensive set of data was to begin with the selection of approximately 20 jet fuels, alternative feedstocks, and blends. Sample selection was done in conjunction with the CRC technical committee to obtain maximum coverage of the fuel specification density range (e.g. 775 to 840 kg/m<sup>3</sup>) and product type/grade (e.g., Jet A, Jet A-1, JP-4, JP-5, F-24, TS-1, and synthetics). Other fuel property considerations included: flash point, additive content, i.e., fuel system icing inhibitor (FSII), corrosion improver/lubricity improver (CI/LI), and static dissipater additive (SDA), and chemical composition, e.g., aromatic content. Table 1 lists the 20 samples that were selected which include a mixture of historic, commercial, military, and alternative jet fuels as well as some synthetic blend components.

*Table 1. List of Samples by Grade<sup>A</sup> and ID Numbers*

No.	Sample POSF ID	Type/ Grade	Aromatics (%vol)	Notes
1	10903	JP-4	15.9	Historic fuel used as baseline
2	10264	JP-8	11.2	Low density, NJFCP <sup>‡</sup> "best case" (A-1) fuel
3	10325	Jet A	17.5	Avg density, NJFCP <sup>‡</sup> "avg case" (A-2) fuel
4 <sup>B</sup>	10289	JP-5	18.6	High density, NJFCP <sup>‡</sup> "worst case" (A-3) fuel
5	13333	F-24	15.2	
6 <sup>B</sup>	5237	Jet A-1	18.8	
7 <sup>B</sup>	8451	JP-8	18.8	POSF 5237 + MIL Additives <sup>†</sup>
8 <sup>B</sup>	12402	No. 3 Jet	5.9	Low aromatic jet fuel
9	10400	JPTS	11.6	Narrow cut jet fuel
10	3327	JP-7	1	Narrow cut jet fuel
11 <sup>C</sup>	13300	JP-10	0	Single compound jet fuel
12 <sup>B</sup>	12376	IPK/A	17.7	Fully synthetic jet fuel
13	13676	CHCJ-5	20.7	
14 <sup>B</sup>	12361	SIP	0	
15 <sup>B</sup>	11714	HEFA	0.1	
16	14004	AVGAS	13.8	100 LL
17 <sup>B</sup>	11769	Jet A	22.1	High aromatic jet fuel
18	13978	HEFA Blend	8.8	50/50 (v/v) Blend of POSF 11714/10325
19	13995	TS-1	12.5	
20	14064	Jet C-1	17.1	75/25 (v/v) Blend of POSF 10325/10903

<sup>A</sup>Descriptions of each fuel grade, along with specifications, are listed in Appendix I.

<sup>B</sup>Detailed compositional data for these fuel samples were generated for CRC Project No. AV-19-14 and are reported by West et al., *Energy & Fuels*, **2018**; POSF ID can be used to cross-reference fuel samples. Note: fuel samples POSF 12361 (this report) and POSF 12398 (West et al., 2018) are equivalent.

<sup>C</sup>Data for JP-10 are contained in a separate report (UDR-TR-2021-161).

<sup>‡</sup>NJFCP = National Jet Fuel Combustor Program

<sup>†</sup>MIL Additives = military turbine fuel additive package includes: FSII, SDA, and CI/LI

Table 2 lists the properties determined in this study along with the method of determination. With the exception of gas solubility, all of the desired fuel properties could be determined using ASTM standard methods. Replicate testing was performed on select samples to demonstrate the precision of generated data when ASTM precision statements were unavailable.

*Table 2. Fuel Properties to Determine and Methods of Measurement*

<b>Fuel Property</b>	<b>Method</b>	<b>Temperatures (°C)</b>
Distillation	ASTM D2887	n/a
Density	ASTM D4052	-40, -20, 0, 10, 30
Viscosity	ASTM D7042	-40, -20, 0, 10, 30
Flash Point	ASTM D56 or D93	n/a
Vapor Pressure (Method 1)	ASTM D6378	25, 37.8, 54.4, 65.6
Vapor Pressure (Method 2)	ASTM D2879	25, 37.8, 54.4, 65.6
Gas Solubility	UDRI FC-M-103	ambient

Flash point measurements (ASTM D56 and/or ASTM D93) and vapor pressure measurements by ASTM D6378 were sub-contracted to Intertek–Caleb Brett (Deer Park, TX) and SGS North America (Deer Park, TX), respectively. All other measurements were performed by UDRI.

Distillation was performed using the gas chromatography method ASTM D2887. An Agilent 7890A GC-FID, configured with a 30-m x 250- $\mu$ m x 0.25- $\mu$ m DB-5 capillary column and hydrogen carrier gas, was used for these analyses. Agilent GC ChemStation software was used to acquire the GC-FID data, which was then analyzed via the WMI SimDis DCS (SIMDIS) software to produce the boiling point ranges for each fuel. In the SIMDIS software, the GC-FID data of a qualitative standard, composed of normal alkanes ranging from C5-C44, was first analyzed to calibrate retention times with the known boiling points of each compound. Once calibrated, the analysis for each sample was automated within the SIMDIS software by performing baseline subtraction, integration, and finally translating retention times to the resulting simulated distillation data.

Sample density and kinematic viscosity were measured using an Anton Paar model SVM 3001 Stabinger viscometer. This instrument provided both ASTM D7042 viscosity and ASTM D4052 density measurements simultaneously. Data collection started at 30°C, with subsequent data collected at progressively lower temperatures across the following range of temperatures: 30, 10, 0, -20, and -40°C.

Fuel sample vapor pressure was measured in-house by ASTM D2879 (isoteniscope with modifications). Fuel samples were degassed by drawing vacuum, at ambient temperature, (typically to less than 1 Torr) prior to analysis using an Alcatel model 2010 SD pump. The volume changes of the samples due to degassing were ca.  $\leq$ 5%, even for the most volatile samples, and was considered consistent with the loss of fixed gases (not evaporation of significant hydrocarbon sample). Data were collected by starting at the lowest temperature in the range, allowing the sample to equilibrate, then reading the pressure using an MKS Instruments, model 902B piezo transducer. After two consecutive pressure readings (each

within ca.  $\pm 0.2$  Torr and about 5 minutes apart) the sample bath temperature was increased incrementally over the following range, with measurements repeated at each temperature: 20, 37.8, 54.4, and 65.6°C. ASTM D2879 was observed with two notable deviations from the method: 1) a constant temperature *liquid* bath (i.e., water) was used instead of an air bath, and 2) a combination of two different sized isoteniscopes were used for testing based upon sample volatilities. Figure 1 shows the smaller isoteniscope, as defined by ASTM D2879, that holds about 3 mL of sample; this isoteniscope was used for samples with lower total vapor pressures. Figure 2 shows the larger isoteniscope, as described by Chen et al., 2016, that holds about 40 mL of sample and was used for higher vapor pressure samples, e.g., JP-4 and AVGAS. Care was taken to minimize the amount of time (and volume lost) during degassing of the more volatile samples; sample volumes were monitored before and after testing to ensure minimal sample loss occurred over the course of the experiment.

Gas solubility was determined using an in-house gas chromatography (GC) method with mass spectrometry (MS) detection, UDRI method number: FC-M-103 [UDR-TR-2019-113, 2017]. Briefly, the method for determining the solubility of fixed gases (e.g., O<sub>2</sub>, N<sub>2</sub>, and Ar) in hydrocarbon fuels involves external calibration of the response with pure hydrocarbon standards. The response from the standard hydrocarbons is used to determine absolute concentrations of the dissolved gases in the samples. Samples and standard fluids were equilibrated prior to analysis under the following conditions: 1) air at ambient conditions (T = 293 K, P = 1 atm), 2) pure nitrogen gas at ambient conditions (T = 293 K, P = 1 atm), and 3) air at P = 1 atm and T = [5, 22, 40°C]. All twenty fuel samples were analyzed under equilibrium conditions 1 and 2. Three fuel samples were analyzed under equilibrium condition 3; selection of these samples was across a range of anticipated volatilities, e.g., JP-4 (high volatility), Jet A (middle volatility), and JP-5 (low volatility). Care was taken for analysis of condition 3 samples to ensure analyzed gas levels were representative of equilibrium conditions by immediate, manual injection of samples taken from the equilibrated vials.

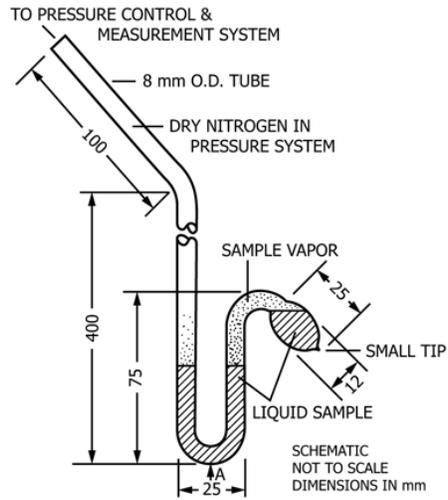


Figure 1. Schematic of the small volume isoteniscope for vapor pressure measurement [ASTM D2879].

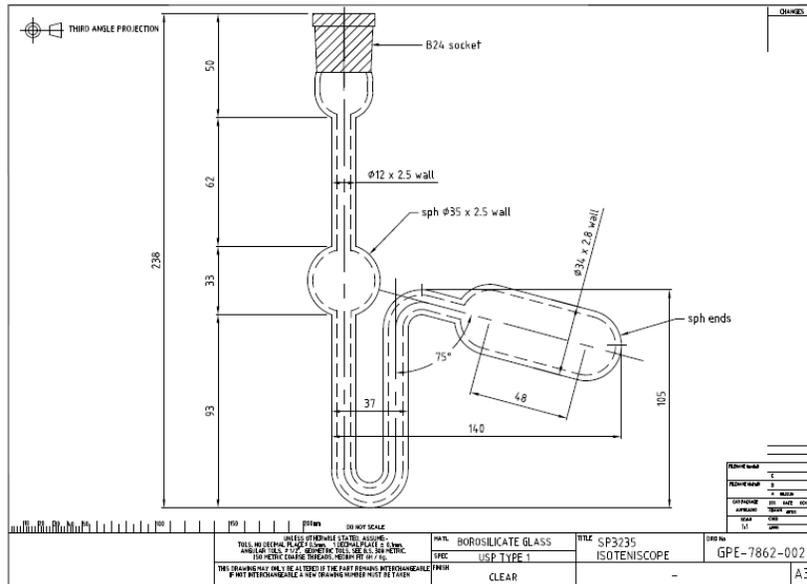
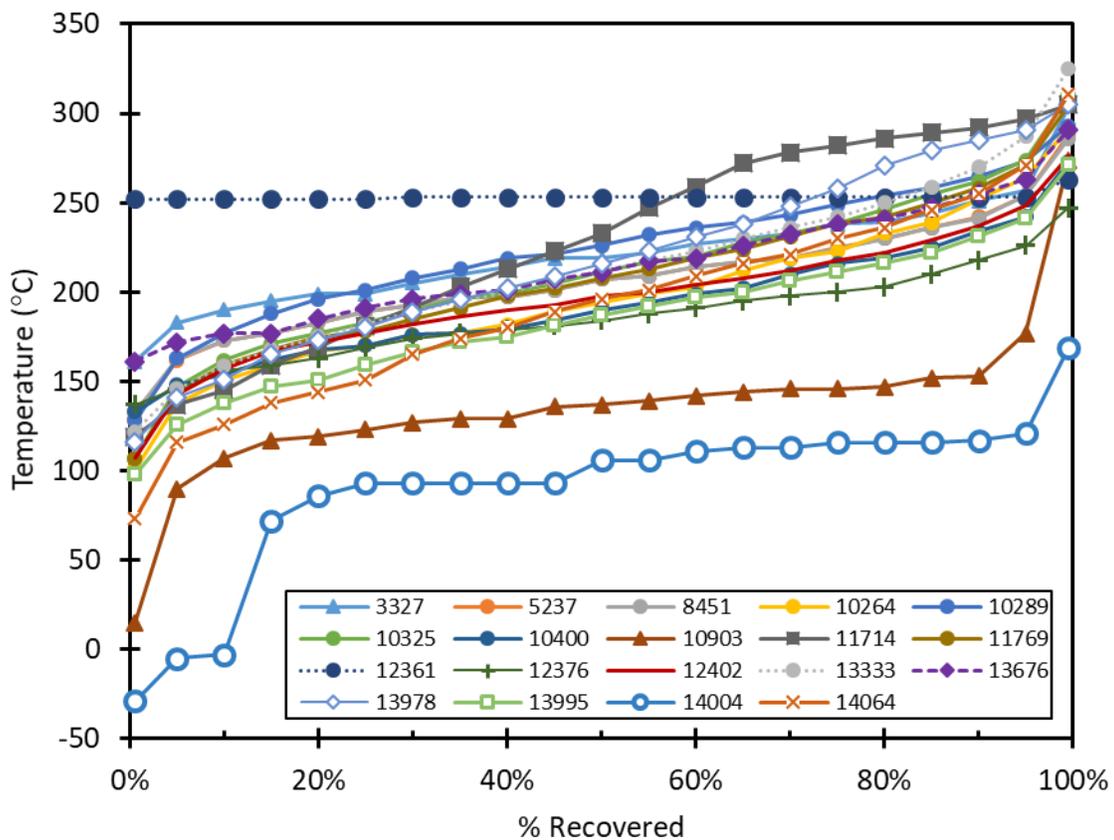


Figure 2. Schematic of the large volume isoteniscope for vapor pressure measurement [Chen et al., 2016].

## RESULTS AND DISCUSSION

### Distillation

Distillation was performed on the samples using the gas chromatography method ASTM D2887; tabulated values are listed in Table 3 and the distillation curves are shown in Figure 3. As the figure shows, the JP-4 (F10903) and AVGAS (F14004) samples demonstrate considerably lower distillation profiles than all other samples. This is expected as these fuel samples were anticipated to be the most volatile. Additionally, the SIP (F12361) sample exhibit a flat distillation profile due to the nature of this sample, i.e., single component. The remaining samples appear grouped within a band of about 50 to 75°C. These data demonstrate the broad spectrum of fuel samples selected.



*Figure 3. Distillation profiles using ASTM D2887.*

*Table 3. ASTM D2887 Distillation Results*

POSF ID	Type/ Grade	Distillation (°C) at % Off																				
		0.5% (IBP)	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%	99.5% (FBP)
10903	JP-4	15	90	107	117	119	123	127	129	129	136	137	139	142	144	146	146	147	152	153	177	274
10264	JP-8	101	138	151	159	167	170	176	177	182	189	194	199	203	212	219	223	233	239	252	264	292
10325	Jet A	107	147	162	171	177	183	190	196	199	205	211	217	220	228	233	238	246	255	262	274	310
10289	JP-5	128	163	177	188	196	201	208	213	219	221	226	232	236	239	243	249	254	258	265	273	293
13333	F-24	122	146	159	168	175	182	189	195	200	206	212	218	223	230	236	242	250	259	270	287	325
5237	Jet A-1	129	162	173	177	183	189	193	197	197	201	207	209	214	217	219	225	230	236	242	254	288
8451	JP-8	133	163	173	177	183	189	193	197	197	201	207	209	214	217	219	224	230	236	241	254	286
12402	No. 3 Jet	107	143	157	167	172	177	182	186	190	193	198	200	204	208	212	218	222	229	237	248	276
10400	JPTS	133	148	154	162	168	170	176	177	179	184	190	194	199	202	210	216	219	225	234	242	273
3327	JP-7	161	183	190	195	199	199	205	210	214	219	219	222	227	230	233	238	239	244	251	257	304
12376	IPK/A	137	146	156	159	163	169	174	177	179	181	184	188	191	195	198	200	203	210	218	226	247
13676	CHCJ-5	161	172	177	177	185	191	196	199	201	207	211	217	219	226	232	238	241	247	255	263	291
12361	SIP	252	252	252	252	252	252	253	253	253	253	253	253	253	253	253	253	253	253	253	253	263
11714	HEFA	119	137	145	159	169	181	191	203	213	223	233	247	259	272	278	282	286	289	292	297	305
14004	AVGAS	-29	-5	-3	72	86	93	93	93	93	93	106	106	111	113	113	116	116	116	117	121	169
11769	Jet A	107	144	159	168	175	178	185	191	198	202	208	213	219	224	231	238	242	250	258	271	305
13978	Blend	116	141	151	165	173	180	189	196	202	209	216	223	231	238	248	258	271	279	285	291	305
13995	TS-1	98	126	138	147	151	159	166	172	175	181	187	192	197	200	206	211	216	222	231	241	271
14064	Jet C-1	73	116	126	138	144	151	165	174	180	189	196	201	209	216	221	230	236	246	255	271	311

## Viscosity & Density

Kinematic viscosity,  $\nu$ , (ASTM D7042) and sample density,  $\rho$ , (ASTM D4052) values were measured simultaneously over the temperature range of 30°C to –40°C and are listed in Table 4. Both fluid properties exhibit anticipated trends with respect to temperature, i.e., density is inversely proportional to temperature, and the log of kinematic viscosity is linearly correlated to the inverse temperature (see Figure 4). Properties exhibited a broad range based on the samples selected, for instance  $\nu$  (at 15°C) ranged from 0.61 to 4.05 mm<sup>2</sup>/s and  $\rho$  (at 15°C) ranged from 0.710 to 0.827 g/cm<sup>3</sup>.

**Table 4. Kinematic Viscosity (ASTM D7042) and Density (ASTM D4052) Results**

POSF ID	Type/Grade	Kinematic Viscosity (mm <sup>2</sup> /s) at Temperature (°C)					Density (g/cm <sup>3</sup> ) at Temperature (°C)				
		30	15	0	-20	-40	30	15	0	-20	-40
10903	JP-4	0.71	0.83	0.99	1.39	2.09	0.7546	0.7674	0.7796	0.7957	0.8119
10264	JP-8	1.30	1.63	2.14	3.45	6.49	0.7687	0.7803	0.7913	0.8062	0.8212
10325	Jet A	1.51	1.93	2.61	4.44	9.12	0.7921	0.8033	0.8143	0.8290	0.8439
10289	JP-5	1.83	2.41	3.38	6.11	14.12	0.8154	0.8266	0.8374	0.8519	0.8666
13333	F-24	1.64	2.12	2.90	5.02	10.64	0.8129	0.8241	0.8352	0.8498	0.8646
5237	Jet A-1	1.47	1.86	2.49	4.18	8.42	0.7850	0.7965	0.8074	0.8221	0.8369
8451	JP-8	1.46	1.85	2.48	4.16	8.40	0.7852	0.7964	0.8074	0.8223	0.8371
12402	No. 3 Jet	1.40	1.77	2.34	3.84	7.35	0.7923	0.8038	0.8148	0.8297	0.8446
10400	JPTS	1.24	1.55	2.03	3.23	6.00	0.7635	0.7751	0.7860	0.8010	0.8160
3327	JP-7	1.83	2.39	3.31	5.89	13.17	0.7819	0.7930	0.8037	0.8181	0.8326
12376	IPK/A	1.24	1.55	2.01	3.23	6.03	0.7711	0.7824	0.7936	0.8085	0.8236
13676	CHCJ-5	1.59	2.04	2.77	4.72	9.68	0.8094	0.8207	0.8317	0.8465	0.8614
12361	SIP	2.87	4.05	6.24	13.64	43.01	0.7612	0.7721	0.7826	0.7967	0.8109
11714	HEFA	1.84	2.43	3.40	6.14	14.19	0.7525	0.7635	0.7742	0.7886	0.8031
14004	AVGAS	0.53	0.61	0.72	0.96	1.31	0.6971	0.7103	0.7234	0.7401	0.7569
11769	Jet A	1.47	1.86	2.50	4.20	8.42	0.8006	0.8121	0.8231	0.8380	0.8529
13978	Blend	1.67	2.17	2.97	5.20	11.25	0.7721	0.7834	0.7944	0.8088	0.8235
13995	TS-1	1.18	1.46	1.89	2.97	5.30	0.7760	0.7874	0.7987	0.8138	0.8289
14064	Jet C-1	1.22	1.52	1.97	3.13	5.72	0.7830	0.7944	0.8058	0.8209	0.8360

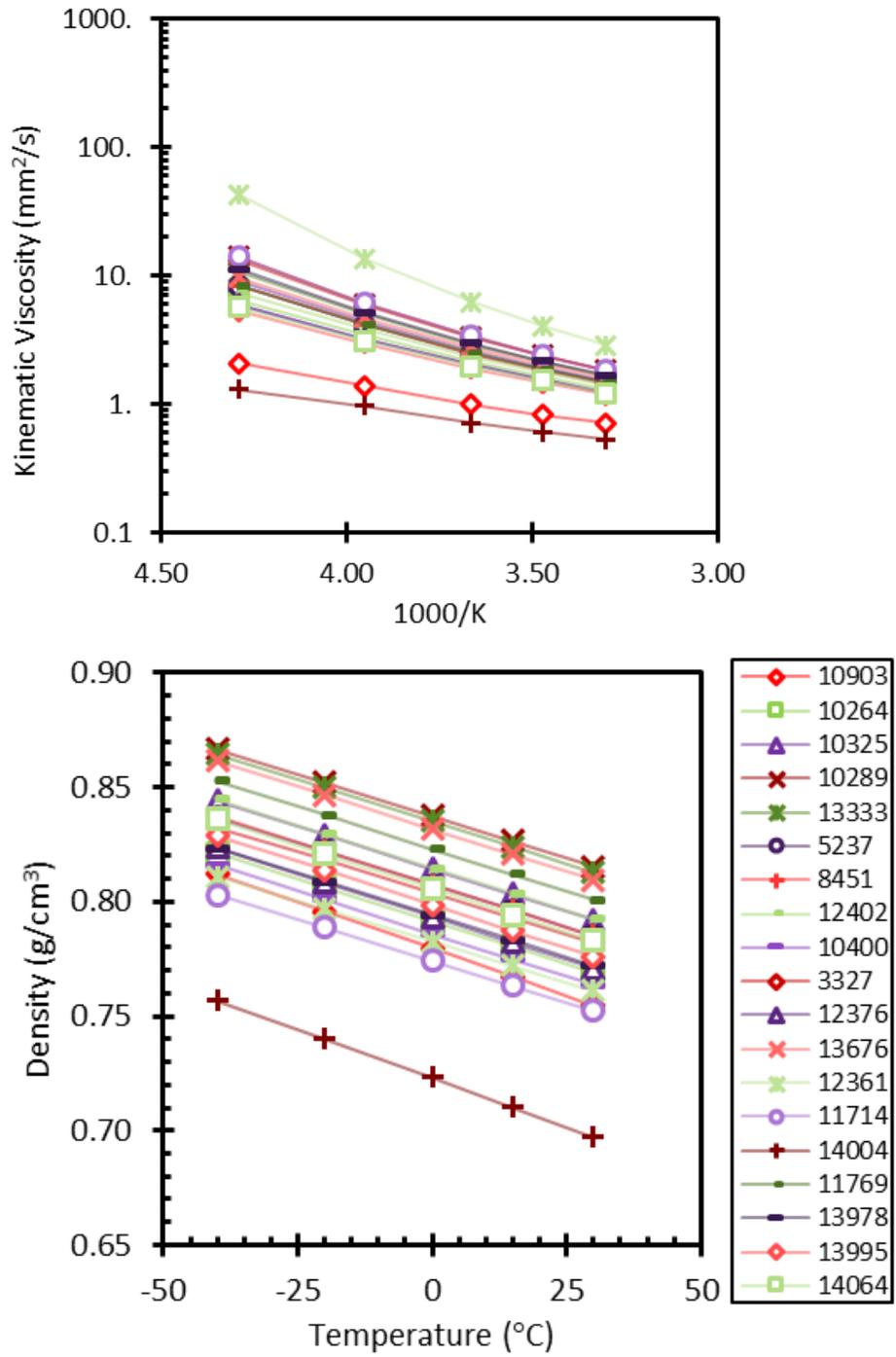


Figure 4. (a) Kinematic viscosity (ASTM D7042) and (b) density (ASTM D4052) profiles.

## Flash Point

Flash point was measured by Intertek–Caleb Brett (Deer Park, TX) using ASTM D56 for all but two samples (ASTM D93 was used for samples F5237 and F12361) and the results are listed in Table 5. Two samples, F10903 and F14004, were reported to have flash points at (or below) ambient temperature; the flash point of these two samples was anticipated to be low due to the volatile nature of the samples. The highest reported flash point was that of F12361 at 107°C and the lowest reported value was for F14064 at 14.5°C.

*Table 5. Flash Point Values by ASTM D56*

<b>POSF ID</b>	<b>Type/Grade</b>	<b>Flash Point (°C)</b>
<b>10903</b>	JP-4	Ambient
<b>10264</b>	JP-8	42.5
<b>10325</b>	Jet A	55.0
<b>10289</b>	JP-5	58.5
<b>13333</b>	F-24	46.0
<b>5237</b>	Jet A-1	60 <sup>†</sup>
<b>8451</b>	JP-8	57.5
<b>12402</b>	No. 3 Jet	42.5
<b>10400</b>	JPTS	45.5
<b>3327</b>	JP-7	69.0
<b>12376</b>	IPK/A	45.5
<b>13676</b>	CHCJ-5	61.0
<b>12361</b>	SIP	107 <sup>†</sup>
<b>11714</b>	HEFA	43.5
<b>14004</b>	AVGAS	Ambient
<b>11769</b>	Jet A	42.5
<b>13978</b>	Blend	44.5
<b>13995</b>	TS-1	35.0
<b>14064</b>	Jet C-1	14.5

<sup>†</sup>Measured using ASTM D93 instead of ASTM D56.

## Vapor Pressure

Vapor pressure was measured using two different techniques: ASTM D6378 (triple expansion method) and ASTM D2879 (isoteniscope method); Table 6 and Table 7 list data obtained from these methods, respectively. A notable difference between these methods is that D2879 involves degassing the sample (to remove dissolved air) prior to the measurement, while D6378 relies upon the ideal gas law to numerically subtract out the contribution of air in the sample vapor pressure. Since measurement of vapor pressure using D2879 was performed using an in-house custom apparatus, validation of results from the apparatus are shown in Appendix V. ASTM D6378 has reported precision information (D6378, section 16, Tables 3 & 5) referenced in the method; however, D2879 does not provide precision information within the method. Therefore, included in Table 7 are the mean (AVG), standard deviation ( $\sigma$ ), type A uncertainty multiplied by a coverage factor of  $k = \text{Student's } t\text{-distribution for a 95\% confidence level (U)}$  [JCGM, 2008], and number of observations ( $n$ ) for each measurement condition.

*Table 6. Vapor Pressure Values via ASTM D6378*

POSF ID	Type/Grade	Vapor Pressure, ASTM D6378 (kPa) at Temperature (°C)			
		25.0	37.8	54.4	65.6
10903	JP-4	8.00	12.41	21.51	30.61
10264	JP-8	1.65	2.90	4.96	7.17
10325	Jet A	1.38	2.48	4.14	5.93
10289	JP-5	1.24	1.93	2.90	4.00
13333	F-24	0.97	1.65	3.03	4.41
5237	Jet A-1	0.97	1.38	2.34	3.31
8451	JP-8	1.10	1.65	2.48	3.59
12402	No. 3 Jet	1.38	2.07	3.59	5.24
10400	JPTS	1.65	2.48	3.86	5.52
3327	JP-7	0.83	1.38	2.21	3.03
12376	IPK/A	1.38	2.07	3.45	5.10
13676	CHCJ-5	1.38	2.07	3.17	4.27
12361	SIP	1.10	1.52	1.93	2.48
11714	HEFA	1.24	2.07	3.59	4.96
14004	AVGAS	28.96	44.54	74.05	101.49
11769	Jet A	1.10	1.93	3.31	4.96
13978	Blend	1.24	1.93	3.31	4.69
13995	TS-1	1.65	2.48	4.41	6.62
14064	Jet C-1	3.17	4.96	8.69	12.41

*Table 7. Vapor Pressure Values via Isoteniscope Method*

POSF ID	Type/ Grade	Vapor Pressure, ASTM D2879 (kPa) at Temperature (°C)															
		25.0				37.8				54.4				65.6			
		AVG	$\sigma$	U	n	AVG	$\sigma$	U	n	AVG	$\sigma$	U	n	AVG	$\sigma$	U	n
10903	JP-4	11.17	1.06	0.70	11	18.80	0.87	1.39	4	28.40	0.71	0.75	6	34.11	3.28	4.08	5
10264	JP-8	3.94	0.95	0.68	10	7.43	1.63	1.16	10	11.45	2.30	1.46	12	13.13	2.41	1.72	10
10325	Jet A	0.21	0.07	0.05	9	0.51	0.11	0.07	14	1.10	0.14	0.09	12	1.83	0.17	0.18	6
10289	JP-5	0.23	0.15	0.16	6	0.47	0.14	0.15	6	0.95	0.19	0.20	6	1.46	0.24	0.22	7
13333	F-24	0.65	0.12	0.19	4	1.39	0.16	0.25	4	2.40	0.23	0.37	4	3.32	0.32	0.50	4
5237	Jet A-1	0.19	0.05	0.08	4	0.38	0.02	0.03	4	0.84	0.01	0.01	4	1.42	0.01	0.08	2
8451	JP-8	0.21	0.02	0.21	2	0.55	0.01	0.10	2	1.10	0.02	0.14	2	1.71	0.00	0.00	2
12402	No. 3 Jet	0.27	0.02	0.18	2	0.69	0.00	0.00	2	1.02	0.01	0.11	2	1.77	0.02	0.17	2
10400	JPTS	0.66	0.12	1.04	2	1.68	0.08	0.68	2	2.79	0.03	0.05	4	3.75	0.03	0.25	2
3327	JP-7	0.24	0.09	0.08	7	0.63	0.22	0.23	6	1.19	0.36	0.38	6	1.74	0.50	0.52	6
12376	IPK/A	0.59	0.05	0.49	2	1.24	0.02	0.18	2	2.11	0.01	0.02	4	3.09	0.02	0.17	2
13676	CHCJ-5	1.53	0.64	0.46	10	3.67	1.55	1.29	8	6.25	2.62	2.19	8	8.33	3.41	2.85	8
12361	SIP	0.91	0.53	0.55	6	2.61	1.10	1.15	6	4.81	2.04	2.14	6	6.54	2.68	2.14	6
11714	HEFA	0.49	0.13	0.21	4	1.10	0.26	0.41	4	2.06	0.28	0.44	4	2.99	0.26	0.42	4
14004	AVGAS	25.92	0.19	1.69	2	39.81	0.08	0.68	2	62.11	0.17	1.52	2	85.34	0.23	2.03	2
11769	Jet A	0.62	0.10	0.86	2	1.49	0.05	0.42	2	2.37	0.03	0.25	2	3.21	0.02	0.17	2
13978	Blend	0.56	0.16	0.17	6	1.70	0.38	0.40	6	2.97	0.37	0.39	6	4.14	0.36	0.38	6
13995	TS-1	2.97	0.44	0.69	4	7.00	0.18	0.29	4	10.79	0.10	0.15	4	13.57	0.21	0.34	4
14064	Jet C-1	4.05	0.48	4.32	2	8.25	0.31	2.80	2	12.95	0.11	1.02	2	16.58	0.07	0.59	2

$\sigma$  = standard deviation

U = type A uncertainty with k=t-distribution, 95% confidence level [JCGM, 2008]

n = number of observations

Figure 5 shows a comparison of the vapor pressures obtained using the two methods outlined; error bars indicate reproducibility, R, and type A uncertainty, U, for D6378 and D2879 data, respectively. Some differences were observed between the two methods: D6378 gave higher values when at low pressures (about  $\leq 4$  kPa), although many of these lower data values are within the given reproducibility range; and D2879 gave higher values at intermediate pressures ( $\sim 4$ -20 kPa). Differences in the vapor pressure magnitude could be due to the different protocols, i.e., experimental sample degassing versus numerical subtraction of air contribution.

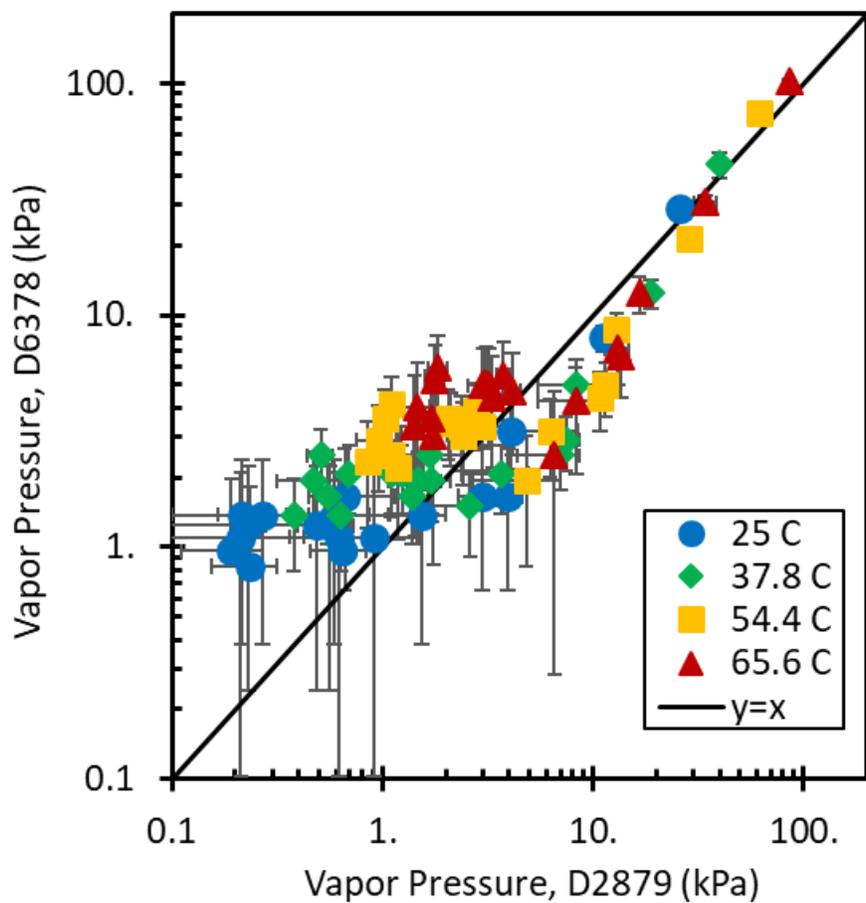


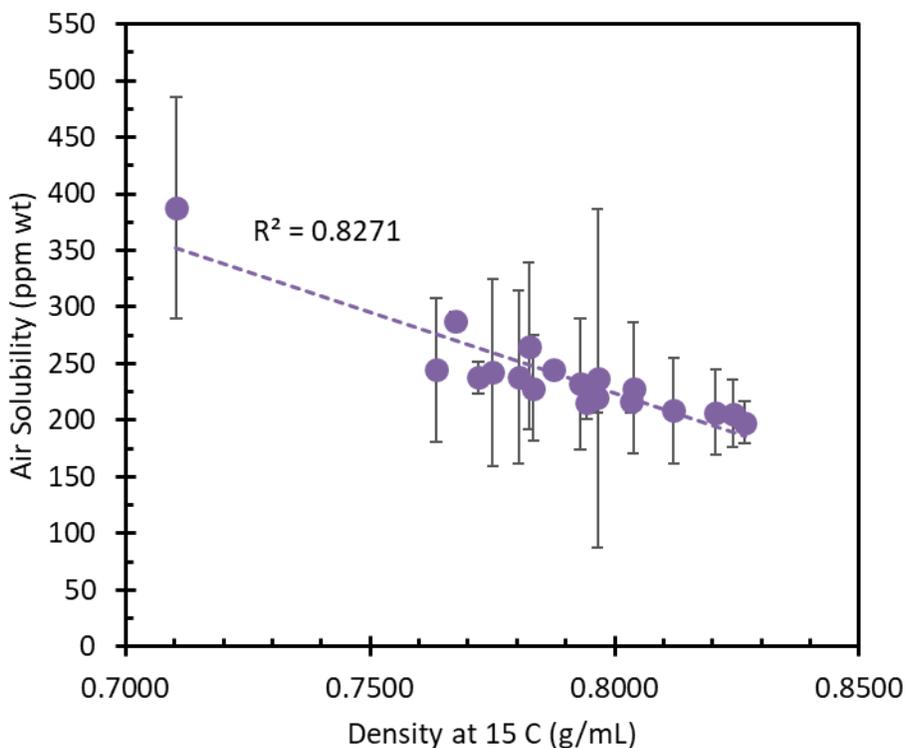
Figure 5. Comparison of vapor pressure measurements by method; error bars indicate reproducibility,  $R$ , and type A uncertainty,  $U$ , for D6378 and D2879 data, respectively.

## Gas Solubility

The dissolved gas solubility of air, i.e., the summation of N<sub>2</sub>, O<sub>2</sub>, and Ar, in fuel samples at standard conditions (293 K and 1 atm) was measured by direct injection using a GC-MS method [West, 2017]. Table 8 reports the gas solubility of each component and the aggregate air amount, reported in parts per million by weight (ppm wt), for each air saturated sample along with the standard deviation,  $\sigma$ , the type A uncertainty with  $k = t$ -distribution at a 95% confidence level, U, and the number of observations, n. The number of observations apply to all individual components since it is a count of the total number of GC-MS injections performed. The values for air solubility are the sum of the three gases;  $\sigma$  and U values for air are computed using standard propagation of error techniques. Figure 6 shows the air solubility data (reported in Table 8) versus sample density at 15°C. As the figure shows, the dissolved gas level is inversely proportional to liquid density, which agrees with previous literature observations [Edwards, 2020; Barnett & Hibbard, 1956].

*Table 8. Dissolved Gas Solubility, Air Saturated, at 293 K and 1 atm*

POSF ID	Type/ Grade	Dissolved Gas Solubility in Air (ppm wt)												n
		N <sub>2</sub>			O <sub>2</sub>			Ar			Air			
		AVG	$\sigma$	U	AVG	$\sigma$	U	AVG	$\sigma$	U	AVG	$\sigma$	U	
10903	JP-4	184.5	3.2	5.2	97.4	3.9	6.3	5.8	0.03	0.1	287.7	5.1	8.1	4
10264	JP-8	151.0	7.6	68.2	81.9	3.8	34.2	5.1	0.04	0.3	238.0	8.5	76.3	2
10325	Jet A	136.2	11.3	10.4	76.2	2.9	2.6	4.8	0.30	0.3	217.2	11.6	10.7	7
10289	JP-5	122.4	2.0	17.9	71.0	0.3	2.6	4.5	0.39	3.5	197.9	2.1	18.4	2
13333	F-24	127.3	3.2	28.9	73.9	0.7	6.2	4.8	0.04	0.3	206.0	3.3	29.5	2
5237	Jet A-1	150.6	16	142.2	80.8	5.1	45.6	5.3	0.40	3.6	236.7	16.6	149.4	2
8451	JP-8	138.9	0.2	1.4	76.8	1.5	13.4	5.0	0.04	0.3	220.6	1.5	13.5	2
12402	No. 3 Jet	143.7	6.2	55.5	79.8	2.0	17.8	5.0	0.04	0.3	228.4	6.5	58.2	2
10400	JPTS	153.3	8.6	77.0	83.4	3.4	30.5	5.5	0.5	4.4	242.1	9.2	82.9	2
3327	JP-7	146.9	6.2	56.1	79.9	1.6	14.1	5.3	0.4	3.6	232.2	6.4	57.9	2
12376	IPK/A	170.4	7.8	70.4	89.3	2.4	21.6	5.7	0.05	0.4	265.4	8.2	73.6	2
13676	CHCJ-5	129.6	4.1	36.5	72.7	1.1	10.2	4.8	0.04	0.3	207.1	4.2	37.9	2
12361	SIP	148.7	1.4	13.0	83.7	0.2	2.1	5.5	0.5	4.5	237.9	1.5	13.9	2
11714	HEFA	154.0	6.4	57.3	85.0	3.0	26.8	5.5	0.5	4.5	244.5	7.1	63.5	2
14004	AVGAS	257.8	58.3	92.8	121.8	19.3	30.7	7.7	1.4	2.2	387.3	61.5	97.8	4
11769	Jet A	130.1	4.9	44.4	73.5	1.4	13.0	4.9	0.04	0.3	208.5	5.2	46.3	2
13978	Blend	143.4	4.8	43.0	79.7	2.0	17.8	5.1	0.04	0.3	228.1	5.2	46.6	2
13995	TS-1	154.3			84.5			5.7			244.5			1
14064	Jet C-1	134.1	5.5	13.6	76.6	1.6	3.9	5.0	0.00	0.0	215.7	5.7	14.2	3



*Figure 6. Air solubility (corrected to 293 K and 1 atm total pressure) versus sample density; error bars indicate the type A uncertainty, U, of measurements.*

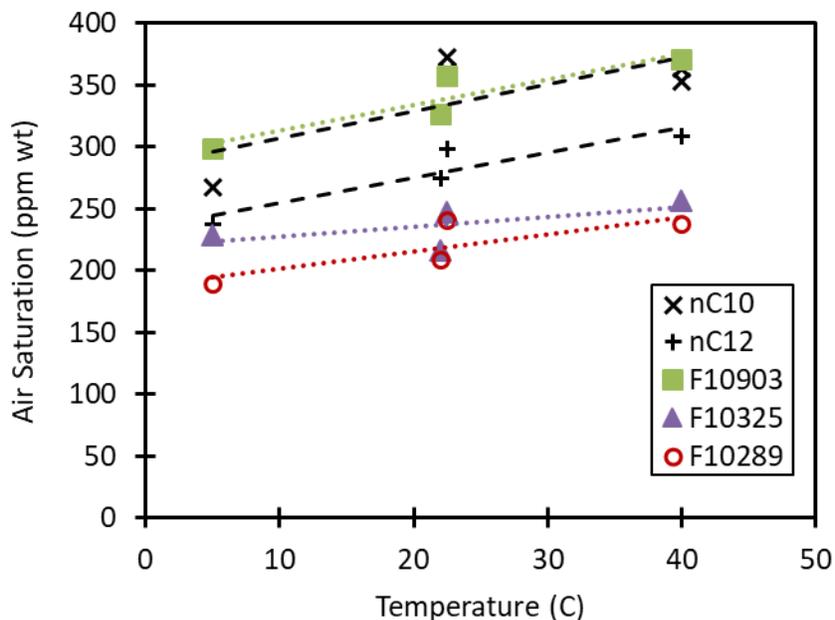
Close examination of the data in Table 8 reveals that the ratios of dissolved gas components are slightly different in the liquid phase compared to the standard gas phase composition of air, e.g., sample F10325 exhibits a liquid phase mass fraction of oxygen of about 0.35 (76.2 ppm O<sub>2</sub> divided by 217.2 ppm Air), while the gas phase oxygen mass fraction for the US Standard Atmosphere (1976) is only about 0.23 (dry basis). The difference in the observed gas ratios in each phase—liquid or gas—is due to the chemical affinity of each gas the respective phase (often called the Henry’s constant). It has been documented that the affinity of typical atmospheric gases in liquid hydrocarbons is in the order: Ar > O<sub>2</sub> > N<sub>2</sub> [Hesse et al., 1996; Edwards, 2020; CRC, 2013]. However, this affinity is not the only deciding factor in total/absolute gas uptake; the partial pressure of each individual gas also plays a role in the dissolved gas amount per Henry’s Law.

The solubility of just nitrogen in each sample was determined by sparging, then equilibrating, samples with pure nitrogen gas at ambient conditions; the values are reported in Table 9. The solubility values obtained in air versus pure nitrogen compare favorably when corrected for the partial pressure of nitrogen gas, that is the nitrogen values reported in Table 8 are approximately 78% of the correlated values reported in Table 9 (the partial pressure of N<sub>2</sub> = 0.78 atm in air at a total pressure of 1 atm). These data reaffirm that Henry’s Law is applicable to describe the gas solubility of N<sub>2</sub>, O<sub>2</sub>, and Ar in fuels under standard conditions.

*Table 9. Nitrogen Solubility at 293 K and 1 atm*

POSF ID	Type/ Grade	Solubility (ppm wt)				POSF ID	Type/ Grade	Solubility (ppm wt)			
		AVG	$\sigma$	U	n			AVG	$\sigma$	U	n
10903	JP-4	250.2			1	12376	IPK/A	212.8			1
10264	JP-8	223.6			1	13676	CHCJ-5	185.7	12.2	30.4	3
10325	Jet A	181.1	7.5	11.9	4	12361	SIP	201.8	2.6	6.5	3
10289	JP-5	203.2			1	11714	HEFA	222.0			1
13333	F-24	172.3			1	14004	AVGAS	416.0			1
5237	Jet A-1	189.6			1	11769	Jet A	234.6			1
8451	JP-8	189.0			1	13978	Blend	194.0			1
12402	No. 3 Jet	191.0			1	13995	TS-1	210.2			1
10400	JPTS	207.7			1	14064	Jet C-1	196.4			1
3327	JP-7	182.2			1						

Additional (brief) studies were conducted on select samples to assess the relative temperature dependence of gas solubility. Samples were equilibrated with air at 1 atm over the temperature range of 5 to 40°C. Figure 7 shows the results of the study for the three fuel samples (F10903, F10325, and F10289) and two reference fluids (n-decane and n-dodecane). As these data show, there appears to be a slight positive temperature dependence to solubility.



*Figure 7. Air solubility trends with sample temperature.*

Considering that density is linearly correlated to temperature (Figure 4b) and air solubility is linearly correlated to density (Figure 6) the solubility data shown in Figure 7 were transformed and are shown as a function of sample density (at the equilibrium temperature) in Figure 8. As

the figure shows two distinct lines of data are observed: a linear trend within the three fuel samples and a separate linear trend within the n-alkanes samples. The observed linear trends further corroborate the link between gas solubility and sample density as was observed in Figure 6. The separation between the n-alkane samples and the fuel samples is attributed to compositional differences, i.e., the fuel samples contain aromatics, cyclo-alkanes, and iso-alkanes in addition to n-alkanes. The observation here that n-alkanes exhibit a lower gas solubility with respect to fluid density, as compared to hydrocarbons with higher degrees of dehydrogenation, has already been documented by Batino et al. for pure hydrocarbons [Wilhelm & Battino, 1973; Field et al., 1974; Byrne et al., 1975; Wilcock et al., 1977; Hesse et al., 1996; Hesse et al., 1999]. Practical implications—for aviation fuels—for this difference in solubility for n-alkanes versus other hydrocarbon types seems minimal when considering many of the other physio-chemical properties, e.g., freeze point, flash point, and viscosity, that must be considered for fully formulated fuels. The practitioner should be aware of these differences due to hydrocarbon type, however, at this time they do not seem concerning.

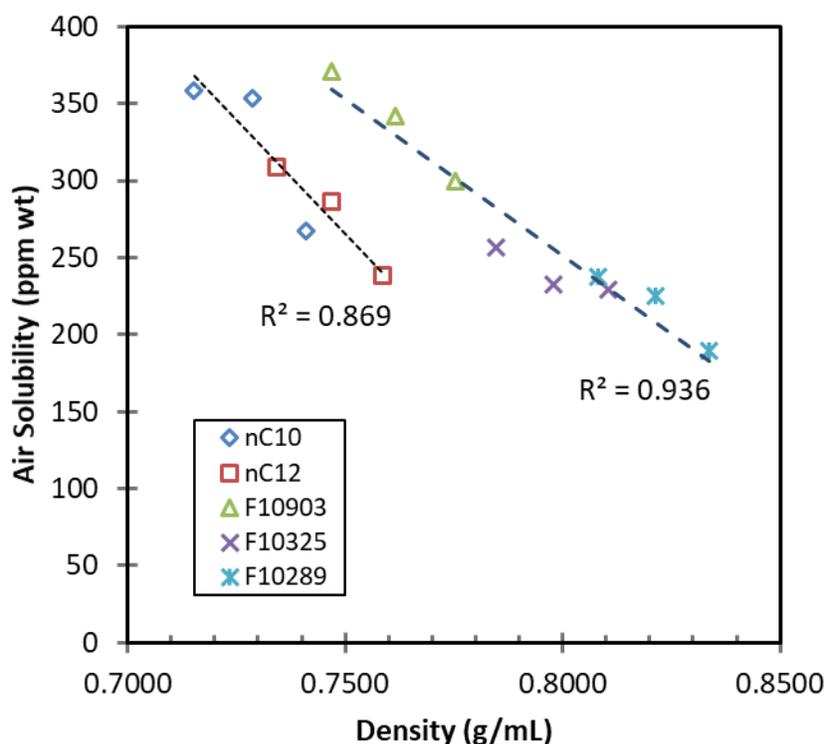


Figure 8. Air solubility versus density of sample at the equilibration temperature; solubility values collected at three different temperatures (ca. 5, 22, and 40 °C) for each sample.

## SUMMARY

The derived V/L ratio parameter is a critical design parameter that requires specific fuel property data, i.e., gas solubility and true vapor pressure. Direct evaluation of the derived V/L ratio parameter, and its application for modern aviation fuels, was not the intention of this study. However, current SAE International publications (AIR1326, ARP492, ARP4024, and ARP4028) often refer to data generated for JP-4 fuel rather than modern kerosene-based turbine fuels such as Jet A and Jet A-1 for the determination of the derived V/L ratio. Therefore, to support a more representative determination of the derived V/L parameter for modern aircraft systems we have experimentally characterized the distillation, density, true vapor pressure, flash point, and gas solubility properties for a robust set of modern jet fuels, alternative feedstocks, and blend mixtures. These data can be used, along with system specific information, to compute V/L ratios for design purposes.

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## NOMENCLATURE

AFRL	=	Air Force Research Laboratory
AVG	=	Average
AVGAS	=	Aviation Gasoline
B	=	Bunsen Coefficient (volume gas at 32°F and 1 atm/volume of fuel at 60°F)
CI/LI	=	Corrosion Improver/Lubricity Improver Additive
CHCJ	=	Catalytic Hydrothermolysis Jet Fuel
CRC	=	Coordinating Research Council
FID	=	Flame Ionization Detector
FSII	=	Fuel System Icing Inhibitor, i.e., Diethylene Glycol Monomethyl Ether
G	=	Gas solubility, parts-per-million by mass (mg gas/kg fuel)
GC	=	Gas Chromatograph
HEFA	=	Hydroprocessed Esters and Fatty Acids
IPK/A	=	Isoparaffinic Kerosene with Aromatics
JPTS	=	Thermally Stable Aviation Turbine Fuel
k	=	Gas solubility coefficient (gas volume %/mmHg); or coverage factor for uncertainty
MS	=	Mass Spectrometry
MW <sub>i</sub>	=	Molecular weight of species i
n	=	Number of observations
NJFCP	=	National Jet Fuel Combustor Program
P	=	Pressure (atm or mmHg or kPa)
P <sub>i</sub>	=	Partial pressure of gas species i (atm or mmHg)
POSF	=	AFRL fuel identification number prefix, also reported as “POSF ID” or shortened to “F” prior to 5-digit number, e.g., POSF 10903 or F10903
RQTF	=	Fuels and Energy Branch of AFRL
R	=	Reproducibility
S	=	Gas solubility, volume percent (%vol)
SDA	=	Static Dissipater Additive
SIP	=	Synthesized Iso-paraffins from Hydroprocessed Fermented Sugars
TVP	=	True Vapor Pressure (kPa)
U	=	Type A Uncertainty using a coverage factor, k, equal to the Student’s t-distribution
UDRI	=	University of Dayton Research Institute
V/L	=	Vapor-Liquid Ratio

### Greek Letters

$\nu$	=	Kinematic viscosity (mm <sup>2</sup> /s)
$\rho$	=	Density (g/cm <sup>3</sup> )
$\sigma$	=	Standard deviation

### Subscripts

i	=	gas species, i.e., N <sub>2</sub> , O <sub>2</sub> , A <sub>r</sub> , Air (mixture)
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## APPENDIX I: FUEL GRADE DESCRIPTIONS

<b>Fuel Name/ Grade</b>	<b>Specification</b>	<b>Description</b>
Jet A	ASTM D1655	Commercial, kerosene, USA
Jet A-1	ASTM D1655	Commercial, kerosene, USA, lower freezing point
No. 3 Jet	GB6537	Commercial, kerosene, China, Jet A-1 equivalent
TS-1	GOST 10227	Commercial, kerosene, Russia
Jet C-1	ASTM 7223	Commercial, wide-cut kerosene
AVGAS	ASTM D910	Commercial, aviation gasoline
JP-4	MIL-DTL-5624	US Military, wide-cut gasoline type (NATO F-40)
JP-5	MIL-DTL-5624	US Military, high-flash point kerosene (NATO F-44)
JP-7	MIL-DTL-38219	US Military, low volatility kerosene
JP-8	MIL-DTL-83133	US Military, kerosene (NATO F-34)
F-24	NATO	Military, kerosene, JP-8 "equivalent" using Jet A
JP-10	MIL-DTL-87107	US Military, high density synthetic hydrocarbon (exo-tetrahydrodicyclopentadiene)
JPTS	MIL-DTL-25524	US Military, aviation thermally stable turbine fuel
HEFA	ASTM D7566 (Annex A2)	Commercial, synthesized paraffinic kerosene from hydroprocessed esters and fatty acids
SIP	ASTM D7566 (Annex A3)	Commercial, synthesized iso-paraffins from hydroprocessed fermented sugars
IPK/A (SPK/A)	ASTM D7566 (Annex A4)	Commercial, synthesized paraffinic kerosene plus aromatics
CHCJ-5	n/a	Research, synthesized kerosene, synthetic JP-5 equivalent, catalytic hydrothermolysis jet (CHJ) similar to ASTM D7566 Annex 6 with high-flash point

## APPENDIX II: V/L RATIO PARAMETER & GAS SOLUBILITY CONSIDERATIONS

### V/L Ratio Calculations<sup>1</sup>

The vapor liquid ratio (V/L) calculation involves determining the maximum amount of vapor (both air/fixed gases and hydrocarbons) that will come out of solution between two stations within a closed fuel system on an aircraft, e.g., the amount of degassing that may occur in between the fuel tank and the fuel pump due to a drop in the absolute fluid pressure from both hydrostatic and frictional pressure losses. The V/L ratio is a function of both the intrinsic properties of the fuel, i.e., the gas solubility and hydrocarbon vapor pressure, as well as the circumstances and operational parameters of a specific aircraft, e.g., the fuel tank pressure (influenced by altitude and/or barometric pressure), and pressure drop within the fuel system (influenced by piping length, fittings, and fuel flow rate, which are unique to specific aircraft and operating points). Therefore, the V/L ratio cannot be calculated from fuel properties alone. Nevertheless, Equation A2.1 shows the general form of the V/L ratio [AIR1326, 2014]:

$$V/L = 1.54k \frac{P_1 - P_f}{P_f - P_{TVP}} \times \frac{t + 460}{95.8 + 0.07t} \quad (1)$$

Where:

$k$  = Solubility Coefficient of air (gas volume %/mmHg partial pressure)

$P_1$  = Initial Static Absolute Pressure (psia)

$P_f$  = Final Static Absolute Pressure (psia)

$P_{TVP}$  = True Hydrocarbon Vapor Pressure (psia)

$t$  = Fuel Temperature at Final Test Equilibrium (°F)

The two fuel dependent variables in Eqn. 1 are:  $k$  and  $P_{TVP}$ . Measurements of these values (or related values) are reported herein:  $P_{TVP}$  are listed in Table 6 and Table 7, and solubility data for air are listed in Table 8. The gas solubility data listed in Table 8 are reported as a weight fraction,  $G$ , with units of mg gas/kg sample; therefore, these values cannot be applied directly in Eqn. 1. Instead the solubility,  $G$ , must be converted into solubility coefficient,  $k$ , prior to use of Eqn. 1. The remaining variables shown in Eqn. 1, i.e.,  $P_1$ ,  $P_f$ , and  $t$ , are all dependent on the specific aircraft system architecture and operating conditions.

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<sup>1</sup> For a comprehensive review of the vapor-liquid ratio parameter including: historical background, technical rationale, and limitations of use the reader is urged to refer to SAE Aerospace Information Report AIR1326 (Rev. A), *Aircraft Fuel System Vapor-Liquid Ratio Parameter*; SAE International, New York, NY, 2014. The sole purpose of this Appendix is to demonstrate how fuel property data (as measured and reported in CRC Project No. AV-27-18) can be used in the calculation of the V/L parameter, as specified in AIR1326A and related documents.

## Gas Solubility Conversion Equations

The solubility of a gas dissolved in a liquid can be expressed in numerous ways, hence a clear method for converting between the many common forms is desirable. To that end, we shall start with a basic definition for gas solubility (as outlined in AIR1326A) and then set out to define conversion equations for some typical ways of expressing solubility within the aviation fuels industry. A comprehensive review of solubility—definitions and data—is available online through the IUPAC-NIST Solubility Database, v1.1, NIST Standard Reference Database 106 (<https://srdata.nist.gov/solubility/index.aspx>).

It is generally accepted that the solubility of a non-reacting gas in a liquid follows Henry's Law, i.e., the amount of dissolved gas in the liquid is proportional to the partial pressure of the gas in equilibrium above the liquid. This can be denoted mathematically by the expression:

$$S_i = k_i P_i \quad (2)$$

Where:

$S_i$  = volume percent solubility of gas species  $i$  in solution, with the gas volume reported under standard conditions, 32°F and 1 atm partial pressure, and the liquid reported at 60°F (mL gas/mL fuel  $\times$  100% = gas volume %)

$k_i$  = Solubility coefficient of gas species  $i$  (gas volume %/mmHg gas partial pressure)

$P_i$  = partial pressure of gas species  $i$  in the vapor phase in equilibrium with the solution (mmHg)

The volume percent gas solubility parameter,  $S_i$ , is simply the Bunsen Coefficient,  $B_i$ , expressed as a percentage rather than a fraction, i.e.,  $S_i = B_i \times 100\%$ . The subscripts in Eqn. 2 are necessary since each individual gas species,  $i$ , is in equilibrium with itself between the liquid and gas phases, and thus each individual gas species has a unique solubility coefficient,  $k$ , i.e., Henry's Law proportionality constant. This means that equilibrium of gas mixtures, such as air, are really a combination of multiple gas equilibrium in summation. Air is often treated as a pseudo-single component, and while this may be useful for engineering and/or design purposes, it does not fully capture the complexity of the equilibrium condition. Therefore, the practitioner is reminded to pay careful attention to these details as they may impact the mass and/or molar ratios of the final mixed gas compositions.

Nevertheless, assuming that the equilibrium headspace gas is air, we can rearrange Eqn. 2 and solve for the aggregate  $k_{air}$  value as follows:

$$k_{air} = \frac{S_{air}}{P_{air}} = \frac{S_{N_2} + S_{O_2} + S_{Ar} + \dots}{P_{N_2} + P_{O_2} + P_{Ar} + \dots} \quad (3)$$

To simplify the air mixture, we only consider N<sub>2</sub>, O<sub>2</sub>, and Ar, which comprise approximately 99.97% of the atmosphere (according to the US Standard Atmosphere, 1976). The mole fractions of these three components are re-normalized such that they are considered to comprise 100% of the air in equilibrium with the fuel (see Table 10). Therefore, the partial pressures of each gas considered—for a total air pressure, P<sub>air</sub>, equal to 1 atm—become: P<sub>N<sub>2</sub></sub> = 0.7811 atm, P<sub>O<sub>2</sub></sub> = 0.2095 atm, and P<sub>Ar</sub> = 0.0093 atm.

*Table 10. Assumed Air Composition (1 atm dry air)*

Gas Species	Molecular Weight, MW <sub>i</sub> (g/mol)	US Standard Atmosphere (1976) Mole Fraction, Y <sub>i</sub>	Re-normalized Air (mixture) Mole Fraction, y <sub>i</sub>	Gas Partial Pressure, P <sub>i</sub> (atm)
Nitrogen (N <sub>2</sub> )	28.01	0.78084	0.7811	0.7811
Oxygen (O <sub>2</sub> )	32.00	0.209476	0.2095	0.2095
Argon (Ar)	39.95	0.00934	0.0093	0.0093

Again, the individual volume percent gas solubility values, S<sub>i</sub>, are derived from the Bunsen Coefficients, B<sub>i</sub>, which in turn can be determined by the gravimetric gas solubility, G<sub>i</sub>, such that:

$$S_i = B_i \times 100\% \quad (4)$$

$$B_i = 0.0224 \frac{\rho G_i}{MW_i} \quad (5)$$

Where ρ is the density of the fuel at 60°F (kg/L), G<sub>i</sub> is the solubility of gas species i (mg gas i/kg fuel), and MW<sub>i</sub> is the molecular weight of gas species i. The constant 0.0224 is the molar volume of an idea gas at 32°F and 1 atm total pressure (22.4 L/mol) times a unit conversion factor (10<sup>-3</sup> g/mg). Thus, Equations 3 through 5, in combination with measurements listed in Table 8 and the gas partial pressures (listed in Table 10) can be used to determine the k<sub>air</sub> values for the fuels reported herein. The calculated k<sub>air</sub> values can be used to determine V/L ratios as mentioned above. Table 11 lists the measured gravimetric solubility values (as reported in Table 8) along with the calculated values of B<sub>i</sub>, S<sub>i</sub>, and k<sub>air</sub> developed using air (at 1 atm total pressure) as the equilibrium gas. Table 12 lists calculated solubility parameters for pure gas species (at 1 atm partial pressure) as the equilibrium gas, i.e., G<sub>i</sub><sup>o</sup>, B<sub>i</sub><sup>o</sup>, S<sub>i</sub><sup>o</sup>, and k<sub>i</sub><sup>o</sup>. These values are derived by dividing the measured G<sub>i</sub> by the partial pressure of gas species i in air, P<sub>i</sub>, to determine the pure component solubility of species i at 1 atm, G<sub>i</sub><sup>o</sup> (see Eqn. 6).

$$G_i^o = G_i \frac{1 \text{ atm}}{P_i} \quad (6)$$

*Table 11. Measured and Calculated Solubility Values for 1 atm Air (mixture)*

POSF ID	Type/Grade	Measured Gravimetric Gas Solubility, $G_i$ (mg gas/kg fuel)				Bunsen Coefficient, $B_i$ (vol gas/vol fuel)				Volumetric Gas Solubility, $S_i$ (vol% gas)				Solubility Coefficient, $K_{air}$ (mixture) (vol% gas/mmHg)
		N <sub>2</sub>	O <sub>2</sub>	Ar	Air (mixture)	N <sub>2</sub>	O <sub>2</sub>	Ar	Air (mixture)	N <sub>2</sub>	O <sub>2</sub>	Ar	Air (mixture)	
10903	JP-4	184.5	97.4	5.8	287.7	0.113	0.052	0.003	0.168	11.3	5.2	0.3	16.8	0.0221
10264	JP-8	151.0	81.9	5.1	238.0	0.094	0.045	0.002	0.141	9.4	4.5	0.2	14.1	0.0186
10325	Jet A	136.2	76.2	4.8	217.2	0.087	0.043	0.002	0.132	8.7	4.3	0.2	13.2	0.0174
10289	JP-5	122.4	71.0	4.5	197.9	0.081	0.041	0.002	0.124	8.1	4.1	0.2	12.4	0.0163
13333	F-24	127.3	73.9	4.8	206.0	0.084	0.043	0.002	0.129	8.4	4.3	0.2	12.9	0.0169
5237	Jet A-1	150.6	80.8	5.3	236.7	0.096	0.045	0.002	0.143	9.6	4.5	0.2	14.3	0.0189
8451	JP-8	138.9	76.8	5.0	220.6	0.088	0.043	0.002	0.133	8.8	4.3	0.2	13.3	0.0176
12402	No. 3 Jet	143.7	79.8	5.0	228.4	0.092	0.045	0.002	0.139	9.2	4.5	0.2	13.9	0.0184
10400	JPTS	153.3	83.4	5.5	242.1	0.095	0.045	0.002	0.143	9.5	4.5	0.2	14.3	0.0188
3327	JP-7	146.9	79.9	5.3	232.2	0.093	0.044	0.002	0.140	9.3	4.4	0.2	14.0	0.0184
12376	IPK/A	170.4	89.3	5.7	265.4	0.107	0.049	0.003	0.158	10.7	4.9	0.3	15.8	0.0208
13676	CHCJ-5	129.6	72.7	4.8	207.1	0.085	0.042	0.002	0.129	8.5	4.2	0.2	12.9	0.0170
12361	SIP	148.7	83.7	5.5	237.9	0.092	0.045	0.002	0.139	9.2	4.5	0.2	13.9	0.0183
11714	HEFA	154.0	85.0	5.5	244.5	0.094	0.045	0.002	0.142	9.4	4.5	0.2	14.2	0.0187
14004	AVGAS	257.8	121.8	7.7	387.3	0.146	0.061	0.003	0.210	14.6	6.1	0.3	21.0	0.0276
11769	Jet A	130.1	73.5	4.9	208.5	0.084	0.042	0.002	0.128	8.4	4.2	0.2	12.8	0.0169
13978	Blend	143.4	79.7	5.1	228.1	0.090	0.044	0.002	0.136	9.0	4.4	0.2	13.6	0.0179
13995	TS-1	154.3	84.5	5.7	244.5	0.097	0.047	0.003	0.146	9.7	4.7	0.3	14.6	0.0192
14064	Jet C-1	134.1	76.6	5.0	215.7	0.085	0.043	0.002	0.130	8.5	4.3	0.2	13.0	0.0171

*Table 12. Calculated Solubility Values for Pure Component Gases at 1 atm Partial Pressure*

POSF ID	Type/Grade	Gravimetric Gas Solubility, $G_i^\circ$ (mg gas/kg fuel)			Bunsen Coefficient, $B_i^\circ$ (vol gas/vol fuel)			Volumetric Gas Solubility, $S_i^\circ$ (vol% gas)			Solubility Coefficient, $k_i^\circ$ (vol% gas/mmHg)		
		N <sub>2</sub>	O <sub>2</sub>	Ar	N <sub>2</sub>	O <sub>2</sub>	Ar	N <sub>2</sub>	O <sub>2</sub>	Ar	N <sub>2</sub>	O <sub>2</sub>	Ar
10903	JP-4	236	465	625	0.145	0.250	0.269	14.5	25.0	26.9	0.0191	0.0328	0.0354
10264	JP-8	193	391	548	0.121	0.214	0.240	12.1	21.4	24.0	0.0159	0.0281	0.0316
10325	Jet A	174	364	514	0.112	0.205	0.232	11.2	20.5	23.2	0.0147	0.0269	0.0305
10289	JP-5	157	339	485	0.104	0.196	0.225	10.4	19.6	22.5	0.0136	0.0258	0.0296
13333	F-24	163	353	519	0.107	0.203	0.240	10.7	20.3	24.0	0.0141	0.0268	0.0316
5237	Jet A-1	193	386	570	0.123	0.215	0.255	12.3	21.5	25.5	0.0162	0.0283	0.0335
8451	JP-8	178	367	537	0.113	0.204	0.240	11.3	20.4	24.0	0.0149	0.0269	0.0316
12402	No. 3 Jet	184	381	532	0.118	0.214	0.240	11.8	21.4	24.0	0.0156	0.0282	0.0316
10400	JPTS	196	398	587	0.122	0.216	0.255	12.2	21.6	25.5	0.0160	0.0284	0.0336
3327	JP-7	188	382	573	0.119	0.212	0.255	11.9	21.2	25.5	0.0157	0.0279	0.0335
12376	IPK/A	218	426	615	0.137	0.233	0.270	13.7	23.3	27.0	0.0180	0.0307	0.0355
13676	CHCJ-5	166	347	521	0.109	0.199	0.240	10.9	19.9	24.0	0.0143	0.0262	0.0316
12361	SIP	190	400	589	0.118	0.216	0.255	11.8	21.6	25.5	0.0155	0.0284	0.0336
11714	HEFA	197	406	596	0.120	0.217	0.255	12.0	21.7	25.5	0.0158	0.0285	0.0336
14004	AVGAS	330	581	833	0.187	0.289	0.332	18.7	28.9	33.2	0.0247	0.0380	0.0436
11769	Jet A	167	351	527	0.108	0.199	0.240	10.8	19.9	24.0	0.0142	0.0262	0.0316
13978	Blend	184	380	546	0.115	0.209	0.240	11.5	20.9	24.0	0.0151	0.0274	0.0316
13995	TS-1	198	403	614	0.124	0.222	0.271	12.4	22.2	27.1	0.0164	0.0292	0.0357
14064	Jet C-1	172	366	541	0.109	0.203	0.241	10.9	20.3	24.1	0.0143	0.0267	0.0317

## APPENDIX III: CERTIFICATE OF ANALYSIS

*Table 13. Intertek–Caleb Brett (Deer Park, TX) Certificate of Analysis Numbers for Flash Point Measurements (ASTM D56 & D93)*

POSF ID	Method	Intertek Reference No.	Sample ID
13995	D56	US785-0070707	2020-DRPK-009101-001
13676	D56	US785-0070707	2020-DRPK-009101-002
10400	D56	US785-0070707	2020-DRPK-009101-004
10903	D56	US785-0070707	2020-DRPK-009101-005
13978	D56	US785-0070707	2020-DRPK-009101-006
11714	D56	US785-0070707	2020-DRPK-009101-007
5237	D93 <sup>A</sup>	US785-0070707	2020-DRPK-009101-008
10289	D56	US785-0070707	2020-DRPK-009101-009
12402	D56	US785-0070707	2020-DRPK-009101-010
12376	D56	US785-0070707	2020-DRPK-009101-011
13333	D56	US785-0070707	2020-DRPK-009101-012
8451	D56	US785-0070707	2020-DRPK-009101-014
10264	D56	US785-0070707	2020-DRPK-009101-015
11769	D56	US785-0070707	2020-DRPK-009101-016
10325	D56	US785-0070707	2020-DRPK-009101-017
12361	D93 <sup>A</sup>	US785-0070707	2020-DRPK-009101-018
14064	D56	US785-0071689	2021-DRPK-001671-001
3327	D56	US785-0071689	2021-DRPK-001671-002
14004	D56	US785-0071689	2021-DRPK-001671-003

<sup>A</sup>Procedure A used.

*Table 14. SGS North America (Deer Park, TX) Certificate of Analysis Numbers for Vapor Pressure (ASTM D6378) Measurements (Order No. 4732809)*

POSF ID	Certificate of Analysis No.			
	25.0°C	37.8°C	54.4°C	65.6°C
10400	DP21-01762.001	DP21-01762.021	DP21-01762.041	DP21-01762.061
14004	DP21-01762.002	DP21-01762.022	DP21-01762.042	DP21-01762.062
12402	DP21-01762.003	DP21-01762.023	DP21-01762.043	DP21-01762.063
14064	DP21-01762.004	DP21-01762.024	DP21-01762.044	DP21-01762.064
13978	DP21-01762.005	DP21-01762.025	DP21-01762.045	DP21-01762.065
13995	DP21-01762.006	DP21-01762.026	DP21-01762.046	DP21-01762.066
5237	DP21-01762.007	DP21-01762.027	DP21-01762.047	DP21-01762.067
11769	DP21-01762.008	DP21-01762.028	DP21-01762.048	DP21-01762.068
13333	DP21-01762.009	DP21-01762.029	DP21-01762.049	DP21-01762.069
12376	DP21-01762.010	DP21-01762.030	DP21-01762.050	DP21-01762.070
10264	DP21-01762.011	DP21-01762.031	DP21-01762.051	DP21-01762.071
12361	DP21-01762.012	DP21-01762.032	DP21-01762.052	DP21-01762.072
13676	DP21-01762.013	DP21-01762.033	DP21-01762.053	DP21-01762.073
10325	DP21-01762.014	DP21-01762.034	DP21-01762.054	DP21-01762.074
10903	DP21-01762.015	DP21-01762.035	DP21-01762.055	DP21-01762.075
11714	DP21-01762.016	DP21-01762.036	DP21-01762.056	DP21-01762.076
3327	DP21-01762.017	DP21-01762.037	DP21-01762.057	DP21-01762.077
10289	DP21-01762.019	DP21-01762.039	DP21-01762.059	DP21-01762.079
8451	DP21-01762.020	DP21-01762.040	DP21-01762.060	DP21-01762.080

## APPENDIX IV: VAPOR PRESSURE (D2879) APPARATUS VALIDATION

Reference fluids (n-decane & toluene) were measured to verify the validity of the isoteniscope method (D2879) and results were compared with literature values as shown in Figure 9. These reference fluids gave excellent agreement to values reported in the literature as well as predictions by the DIPPR 801 database, thus giving confidence to our technique and protocol.

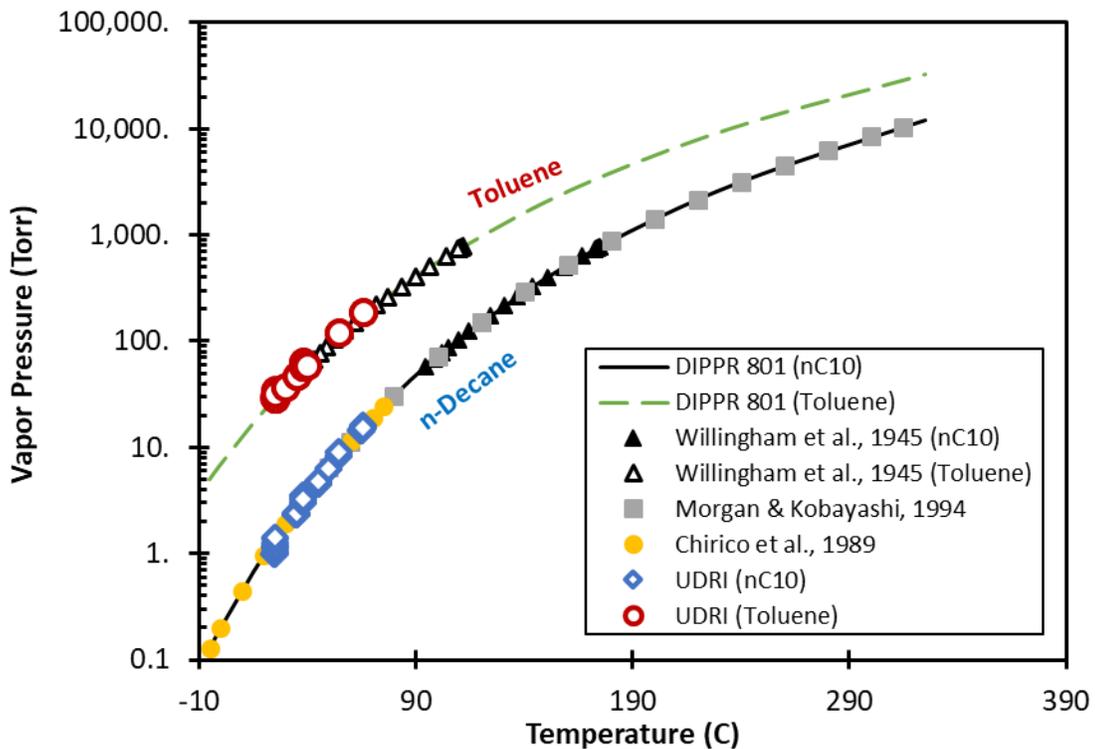


Figure 9. Vapor pressure profiles for toluene and n-decane; UDRI data measured by modified ASTM D2879.