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CALIBRATION CHECK OF FUEL FLOW MEASURING SYSTEM AT ENGINE TEST FACILITY CFB BADEN-SOELLINGEN

W. Grabe, J. Carvish

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CALIBRATION CHECK OF FUEL FLOW MEASURING SYSTEM AT ENGINE TEST FACILITY CFB BADEN-SOELLINGEN

ESSAI D'ÉTALONNAGE DU SYSTÈME DE MESURE DU DÉBIT DE CARBURANT A L'INSTALLATION D'ESSAI DES MOTEURS DE LA BFC DE BADEN-SOELLINGEN

W. Grabe, J. Carvish

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ABSTRACT

An attempt was made to calibrate the fuel flow measuring system at the engine test facility, CFB Baden-Soellingen, by means of transfer standards of the National Research Council Canada. In normal operating mode, with reference meters installed in series in the fuel system, the facility readout displayed extraordinary fluctuations of up to 7270 lbm/h, or 88% of mean flowrate, when the NRCC measuring system indicated stable flow. These instabilities in the ETF flow measuring system precluded any calibration. Flow measurements from the engine core flowmeter were relatively stable and within 0.85% of NRCC data, at maximum flow, but deviated by up to 2.2% from the reference measurement under throttled operation. Recommendations have been made for improvements in the fuel flow calculation method.

RÉSUMÉ

On a tenté d'étalonner le système de mesure du débit de carburant à l'installation d'essai des moteurs, BFC Baden-Soellingen, au moyen d'étalons de transfert du Conseil national de recherches du Canada. En mode normal de fonctionnement, les lectures des appareils de mesure de référence de l'installation des moteurs, montés en série dans le circuit du carburant, ont révélé des fluctuations extraordinaires allant jusqu'à 7270 lbm/h, soit 88% du débit moyen, lorsque le système de mesure du CNRC indiquait un débit stable. Ces irrégularités dans le système de mesure du débit de l'IEM ont rendu tout étalonnage impossible. Les mesures de débit du débitmètre interne du moteur étaient relativement stables, s'écartant au plus de 0,85% des données du CNRC pour un débit maximal, mais présentaient des écarts allant jusqu'à 2,2% par rapport aux mesures de référence pour un fonctionnement au ralenti. Des recommendations ont été faites en vue d'améliorer la méthode de calcul du débit de carburant.

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CALIBRATION CHECK OF FUEL FLOW MEASURING SYSTEM
AT ENGINE TEST FACILITY CFB BADEN-SOELLINGEN

1.0 OBJECTIVE

With the acquisition of the CF18 fighter aircraft by the Canadian Forces, special engine test facilities (ETF), commonly referred to as "Hush Houses", were built at CF Bases Cold Lake, Bagotville, and Baden-Soellingen to permit testing of the General Electric F404 turbofan engine. The test cells will accommodate the bare engine, mounted in an overhead test stand, which includes an air inlet bellmouth, or the whole aircraft.

As part of the commissioning procedure, it was necessary to check the facility fuel flow measuring system for stability and accuracy. The Engine Laboratory, National Research Council Canada, was requested by the Canadian Forces to assist in the calibration of the flow measuring systems at the three bases (Ref. 1). This report deals with the calibration check at the CFB Baden-Soellingen, Germany (Ref. 2).

2.0 INTRODUCTION

The calibration check of the fuel flow measuring system at CFB Baden-Soellingen followed an earlier calibration attempt, in July 1985, at the ETF Bagotville (Ref. 3). The systems were identical except for modifications which had been implemented at the ETF Baden-Soellingen.

A two-man team from the Engine Laboratory carried out the calibration check from 4-6 March 1986, using transfer standard fuel flowmeters, which will be described in some detail below. The test set-up and schedule followed closely the ones established at CFB Bagotville.

3.0 NRCC FUEL FLOW MEASURING SYSTEM

3.1 Method of Fuel Flow Measurement

The method of measuring the fuel flow applied at the calibration check was based on the one employed at the Engine Laboratory. The major difference was that the data were recorded and reduced manually rather than by computer.

The system consisted of a turbine (volume) flowmeter, a frequency counter, a temperature probe, and a temperature indicator. Fuel flow was determined from the meter frequency, the meter calibration, and a volume-to-mass conversion, as follows:

$$WF = \frac{\text{FREQUENCY} \cdot 8.337162 \cdot SG(T_{fuel}) \cdot 3600}{CT \cdot K}$$

Note: With the exception of temperatures, imperial units have been used throughout the report in agreement with the practice at the ETF.

where:

WF = fuel flow, lbm fuel/h

FREQUENCY = flowmeter frequency, pulses/s

SG (T_{fuel}) = specific gravity of the fuel at the temperature of flow measurement, see Appendix A.

$$CT = \frac{1}{(1+3\alpha(T_O-T_C))} = \text{flowmeter thermal correction factor}$$

α = coefficient of thermal expansion of material of meter body (for FTI meters: $17.28 \cdot 10^{-6}$ with temperatures in °C)

T_O = observed fuel temperature, °C

T_C = fluid temperature at calibration, °C (for these tests 23.8° C was used)

For small differences between fuel temperature and the temperature at calibration, the value of CT approaches 1 and may be neglected, e.g. a difference of 1° C will cause a 0.005% difference in fuel flow.

K = flowmeter calibration factor, pulses/US gallon, obtained from calibration as a function of frequency/viscosity

The derivation of the conversion factor 8.337162 is given in Appendix B.

Assuming that the flowmeter frequency output is read accurately and that the flowmeter thermal correction factor, CT, is taken into account, the correct fuel flow measurement depends on the establishment of the true specific gravity of the fuel at temperature of measurement and on the application of the proper K value obtained from calibration.

3.2 Instrumentation and Calibration

The NRCC transfer standard for fuel flow measurement consisted of three separate systems of different flow ranges. The ¾" Flow Technology Inc. (FTI) turbine flowmeter, S/N 1202357, covered a nominal range from 500 to 10,000 lbm/h. The range for the 1" meter, S/N 160507, was 1,500 to 20,000 lbm/h, and that of the 1½" meter was 4,500 to 65,000 lbm/h. All measurement ranges given are approximate, for standard conditions.

The frequencies, obtained from RF pickups, were read on a Fluke 7261A counter, S/N 3795003 [Fig. 1]. The gate was set to yield a resolution of 1 Hertz.

The fuel temperatures were measured by copper-constantan thermocouples and displayed on a Doric temperature indicator, Model 415A, S/N 365571.

Each of the three flowmeters had been calibrated six times on the in-house FTI Omnitrak Flow Calibrator System, Model OT-150. The calibrator, which was acquired and installed during the previous year, has a claimed accuracy of ∓0.1% and a repeatability of ∓0.05%. While the absolute accuracy has not been verified yet, the calibration plots show that, with few exceptions, points fall within a ∓0.05% band, [Figs. 2, 3, 4]. It can be reasonably assumed that the overall accuracy of the three reference flowmeter systems was within ∓0.25% of true values.

4.0 SOME COMMENTS ON THE ETF FLOW MEASURING SYSTEM

Although NRCC was not specifically requested to assess critically the design philosophy of that system, the following are some comments on observed weaknesses of the system.

It is understood that a constant value of 0.76 is used for specific gravity in calculating fuel flow. This simplified approach can introduce significant bias errors, since fuel flow is directly proportional to the specific gravity of the fuel. Using actual specific gravities, calculated from NRCC fuel temperature measurements, maximum errors of 0.90%, 0.85%, and 0.52% were introduced in the ETF flow calculations in test series 10-X, 11-X, and 13-X, respectively. These errors are based on fuel temperatures of 24.0°, 7.3°, and 20.4°C. At a more extreme temperature, say 36°C, the error in specific gravity, and thus fuel flow, would be 2.2%.

For these tests, the specific gravity at standard temperature was 0.7599, or very nearly the value of the constant used. However, the specification limits for JP4 are 0.751 to 0.802 (Spec. CAN 2-3.22-M78), hence, any specific gravity shift towards the limits would contribute to a bias error in the fuel flow calculation of between -1.2 and +5.5%.

While it is not fully understood how the flowmeter calibrations of the ETF system are handled by the data reduction system, apparently the K factor is considered to be constant over the metering range of each meter. This again may lead to inaccuracies in the calculation of flows, because few turbine flowmeters have a perfectly flat calibration curve [Figures 2 to 4]. In the case of the three NRCC meters used in the calibration check, errors of up to ∓0.30% (¾" meter), ∓0.25% (1" meter), and ∓0.17% (1½" meter) could have occurred if a single K value had been used instead of the actual curve.

The above indicated excursions were obtained from the three meters on hand by relating curve values to true means of the curves. If the K factors of the ETF meters do not represent true mean values of their current calibrations, then the bias errors would be further increased.

It is felt that the correct values of specific gravity and flowmeter calibration must be incorporated in the ETF fuel flow calculations to obtain accurate results.

5.0 CALIBRATION SET-UP

The calibration set-up followed closely the one established at CFB Bagotville (Ref. 3). The test set-up took basically two forms. In the first one, the fuel supply line was disconnected at the test stand. The NRCC flowmeters were connected in series to the fuel hose, and on the outlet end to another hose returning the fuel to the fuel tank [Fig. 5]. A throttling valve downstream of the NRCC meters permitted flow adjustment. Thus, fuel was circulated by the LP supply pump through the filters, the ETF facility meters, the test stand accumulator, and the NRCC meters.

In the first part of this test configuration, Series 10-X, all three NRCC meters (¾", 1", and 1½") were used. For the second part, the small and medium size meters were removed, and only the 1½" meter remained in the line for Series 11-X.

In the second test configuration, the fuel line with the 1½" NRCC meter was hooked up to the engine. The engine core fuel line was disconnected and the ¾" and 1" NRCC meters were inserted, in series, just upstream of the integral engine core flowmeter. The tests with this set-up formed Series 13-X.

The tests of Series 12-X, which had the same configuration as Series 11-X, served as facility checks only and were not evaluated for this report.

6.0 DISCUSSION OF CALIBRATION RESULTS

6.1 General

The test data from the ETF system and the NRCC transfer standard were gathered separately by the respective personnel. The facility data were based on a constant specific gravity of 1.0; they were subsequently multiplied by 0.76, the specific gravity constant which is normally used for data reduction.

The NRCC data were reduced as described in sub-section 3.1, following the process used by the Engine Laboratory for in-house fuel flow determination.

Tables 1 to 6b contain raw and reduced data as well as comparative assessments.

6.2 Calibration Series 10-X

The closed-loop tests of Series 10-X served to assess the quality of ETF system flow measurement, unaffected by normal flow fluctuations from engine operation. As well, it provided a means for checking the relative agreement between the three NRCC measuring systems, where their ranges overlapped.

Agreement between the NRCC meters was very good [Table 1b]. The fact that the 1½" meter was barely in range at test points 10-6 and

10-7 accounts for the relatively wide spread of 55 lbm/h, 1.05%. At the the somewhat higher flows, agreement between all three NRCC systems was within 12 lbm/h, 0.20%. The small and medium meters were within 12 lbm/h, 0.23% over the whole test range, with one exception at 19 lbm/h, 0.51%. The readouts were steady, within 1 Hz, which permitted an estimation to within 0.5 Hz, constituting about 0.07 to 0.15% of reading for the small and medium meters.

The ETF reduced data, as supplied to NRCC, were multiplied by the normally used specific gravity constant of 0.76 [Table 2]. Because the flow indications fluctuated, high and low readings were taken. Fluctuations ranged between 12 and 69 lbm/h, or 0.70 and 3.68%, an order of magnitude greater than those of the NRCC systems.

Differences between ETF average values and NRCC flow measurements grew from 1 to 165 lbm/h with increasing flows, the ETF indications being high for the most part. Percentage differences ranged from 0.13 to 2.59%, with the same trend.

Flow indications by the ETF system fluctuated more than expected under steady flow conditions, although the excursions were not exorbitant. The ever-increasing differences between the facility flow measurements and those from the transfer standard seem to point at a bias in the ETF system. Some possible sources of error have been identified in Section 4.0.

6.3 Calibration Series 11-X

The 11-X Series was a continuation of the previous one, with the small and medium NRCC reference meters removed. The minimum flow was the maximum obtained in the 10-X Series, and ranged upwards to 28,000 lbm/h.

Again, the NRCC meter readouts were very steady, within 1 Hz, yielding a readability of ∓0.5 Hz, or ∓20 lbm/h [Table 3]. The ETF flow indications continued to fluctuate, ranging from 46 to 208 lbm/h, and 0.52 to 1.72% [Table 4]. Over the latter half of the series, the oscillations averaged about 0.75% of the mean flow indication.

Following the pattern of the first series, differences between facility and NRCC measurements increased with increasing flows, from 21 to 347 lbm/h, or 0.30 to 1.48% [Table 4]. However, this time the ETF system values were lower than the reference ones.

The general pattern of the facility flow measurement of this series compared well with that of Series 10-X. Measurement fluctuations were larger in actual value, but in percentage of flow they were of similar magnitude. When comparing flow measurement deviations between the ETF and NRCC systems, they were somewhat less in percentage terms than in Series 10-X. However, the deviation trend was opposite to that of the first series, i.e. the ETF flow indications were smaller than the NRCC values. If different flowmeters were used for the two series, opposing calibration curve slopes could be responsible for this phenomenon.

6.4 Calibration Series 13-X

In the second configuration, both the facility (total) fuel supply and the engine gas generator, or "core", flow were measured. The engine was operated over its whole range, from idle to maximum afterburning. The test series was labelled 13-X.

Under these test conditions, some fuel flow fluctuations were observed on the NRCC readout instrument. They were typically:

¾" meter: 1 to 5 Hz → 5 to 26 lbm/h

1" meter: 1 to 4 Hz → 10 to 39 lbm/h

1½" meter: 0 to 1 Hz → 0 to 39 lbm/h
(0.47% at IRP power setting) [Tables 5a & 5c]

Agreement between the two NRCC meters monitoring the core flow was very good, lying between 0 to 28 lbm/h, or 0 and 0.35%, with one excursion of 44 lbm/h [Table 5c]. Most differences were well below 0.20%.

In the non-afterburning regime, the three NRCC meters agreed within 86 lbm/h, or 1.06%. Considering the physical separation of the meter locations in the system and possible effects of the engine fuel control, the differences may be considered acceptable.

The ETF (total) fuel flow readings were characterized by extremely large fluctuations. They ranged between 1430 and 7270 lbm/h, which constituted 88% of the mean flowrate at that point [Table 6a], or 2977 lbm/h and 127% of the first test point. The only major element between the facility meter(s) and the NRCC reference meter was the accumulator, mounted on the test stand. Possibly, a flow instability existed between the LP pump and the accumulator which was not present between the accumulator and the engine, where the reference meter was located.

Although comparison of flow measurements under such conditions becomes somewhat academic, agreement between the average ETF values and the reference system was better than one would expect [Table 6a]. Differences ranged from 1 to 439 lbm/h or 0.01 to 1.62%. For a meaningful assessment of facility flow measurement under engine operating conditions, however, the excessive fluctuations in flow indications must first be eliminated.

Facility flow readings were discontinued after test point 13-10.

The engine core flow was measured by an on-board mass flowmeter, hence no correction for specific gravity was required. The flow indications by the integral engine meter were relatively steady; they fluctuated by between 2 and 164 lbm/h or 0.18 and 2.28% of flow [Table 6b]. With the exception of three larger excursions, the majority of fluctuations were around 0.35%.

When comparing the measurements from the mass flowmeter to the NRCC reference meters, agreement varied between 6 and 124 lbm/h or 0.07 and 4.21% of reading. In general, better agreement existed at maximum gas generator flow, with the engine in the afterburning mode, than at throttled conditions. At maximum flow, differences were about 0.85% of flow, whereas at reduced flows the engine meter readings were lower by between 0.09 and 2.16%, if two idle conditions are neglected.

With the engine in operation, any assessment of the ETF fuel flow measuring system was overshadowed by excessive fluctuations of the ETF DAS system output, while very stable flow conditions were monitored by the NRCC system. The engine core flow measurements were relatively stable but showed significant differences from the two reference meters. Better agreement should be possible.

7.0 SUMMARY AND RECOMMENDATIONS

1. On request by the Canadian Forces, a calibration check of the fuel flow measuring system of the engine test facility CFB Baden-Soellingen was carried out by NRCC personnel, using transfer standard instrumentation.

2. The NRCC flow measuring equipment consisted of three flowmeters of different sizes and ranges, which had been calibrated on an in-house Omnitrak Flow Calibrator System. The flow measuring systems' expected accuracy and repeatability were within ∓0.25%.

3. The test set-up was in two configurations. In the first one, fuel was pumped through the ETF system and the NRCC meter(s) in series, and was returned to the supply fuel tank (Test Series 10-X and 11-X). In the second configuration, the fuel system was hooked up for normal engine operation, with one reference meter installed in the (total) fuel supply line and two reference meters in the core flow system (Test Series 13-X).

4. In the return-loop configuration, the facility system displayed significant fluctuations of between 0.70 and 3.7% of mean readings at lower flows (Series 10-X) and 0.52 to 1.7% at higher rates (Series 11-X). NRCC readings under these conditions were very steady, viz. 0.25% and better.

5. Facility measurements, in this configuration, agreed very well with the reference measurements at the low end, but deviated increasingly towards the higher flow points. Maximum deviations were -165 lbm/h, or -2.6%, in Series 10-X, and 347 lbm/h or 1.5% (at different test points) in Series 11-X.

6. In the second test configuration, with the engine in operation, the ETF system indicated very large fluctuations, ranging from 1430 to 7270 lbm/h, or 5 to 88% of mean flow. At the same time, fluctuations of the NRCC system output were within 1 Hz, which translates into 39 lbm/h, or 0.47% of flow

at IRP power setting. In the light of these fluctuations, flow assessments are rather meaningless.

7. Fuel flow readings from the integrated engine mass flowmeter were relatively stable. While some larger fluctuations were recorded, most of them were around 0.35% of reading. At maximum flow, engine meter readings were within about 0.85% of those from NRCC meters, while under throttled conditions, differences ranged between 0.09 and 2.2%, above idle setting.

8. Before a calibration of the ETF fuel flow measuring system can take place, the cause of the excessive fluctuations displayed must be found and corrected. If the instability cannot be traced to the data acquisition system, then the flow stability between LP pump and accumulator should be investigated.

9. In striving to obtain the most accurate fuel flow measurements from turbine (volume) flowmeters, a critical examination of the calculation method is recommended. It is essential to estimate the correct specific gravity of the fuel at the temperature of flow measurement. Furthermore, the true meter calibration constant K, for a given corrected frequency, should be established and applied in fuel flow computation.

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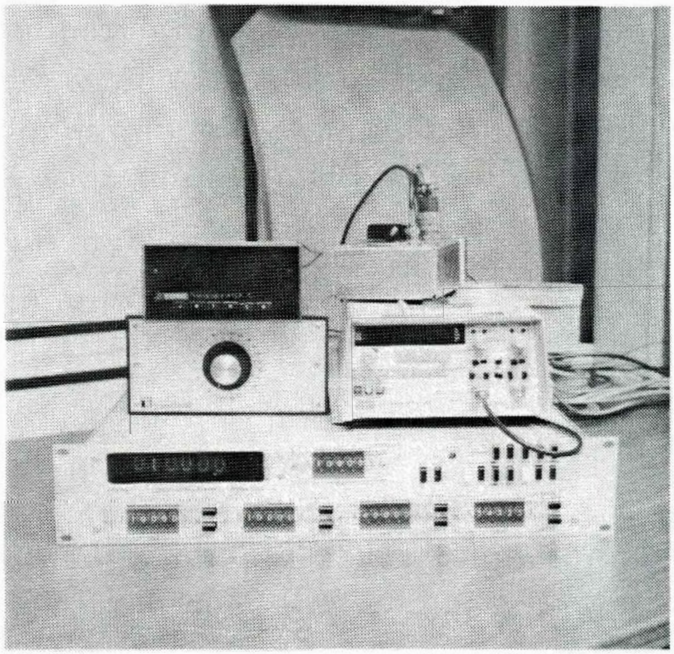


Figure 1: NRCC Frequency Counter and Temperature Indicator

Figure 2: FLOW TECHNOLOGY INC. FLOWMETER CALIBRATION

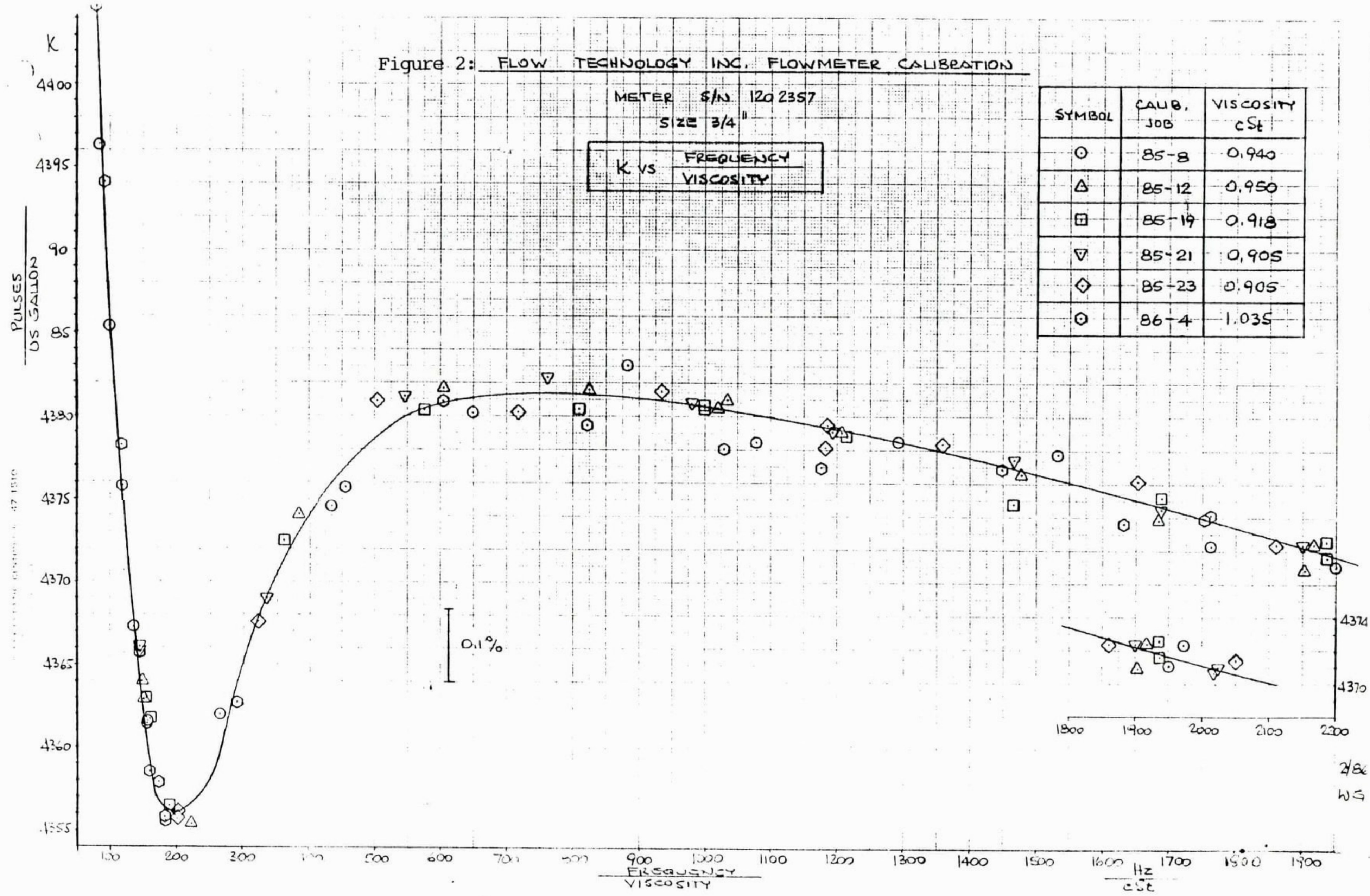
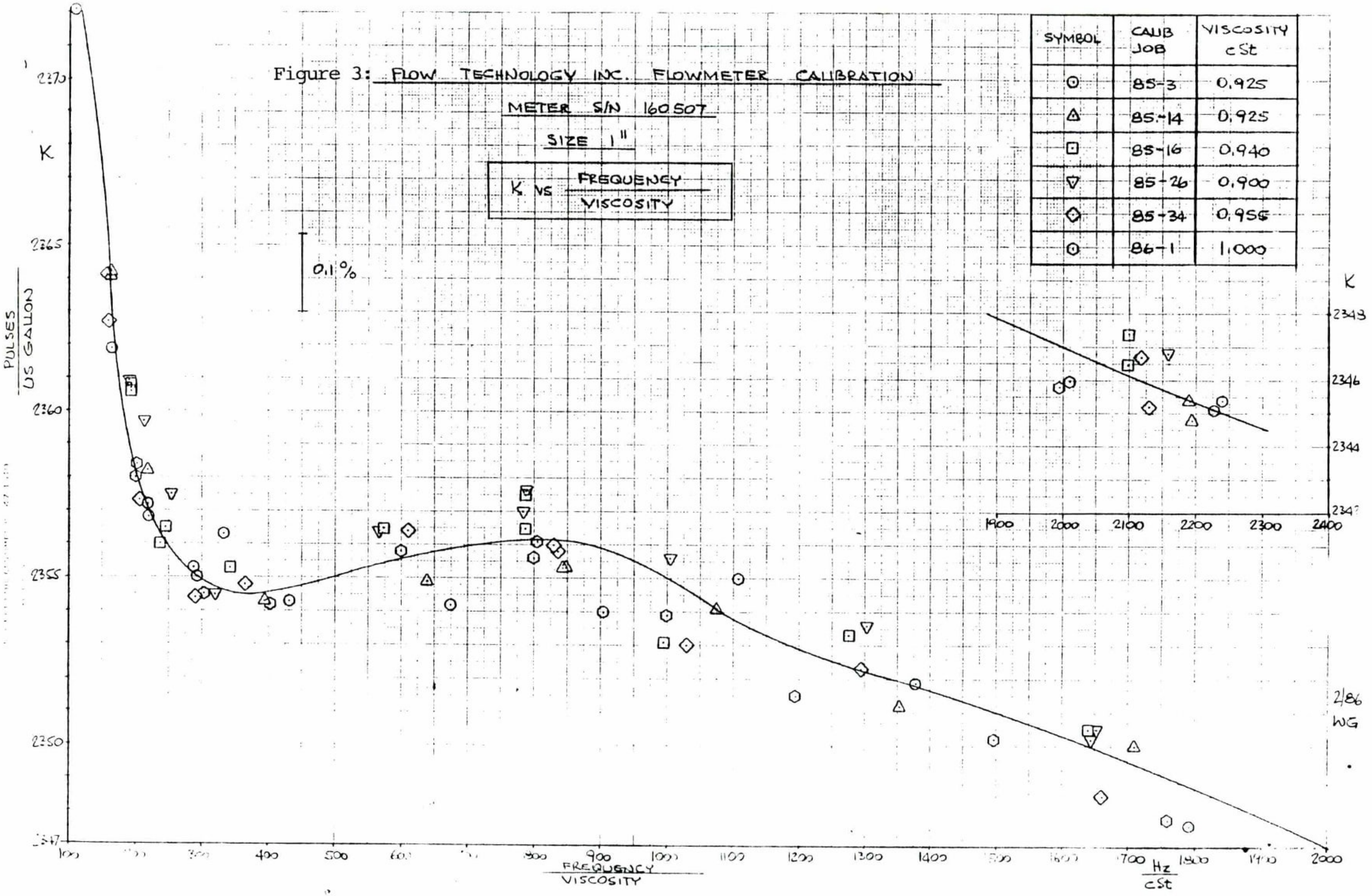


Figure 3: FLOW TECHNOLOGY INC. FLOWMETER CALIBRATION

METER S/N 160507

SIZE 1"



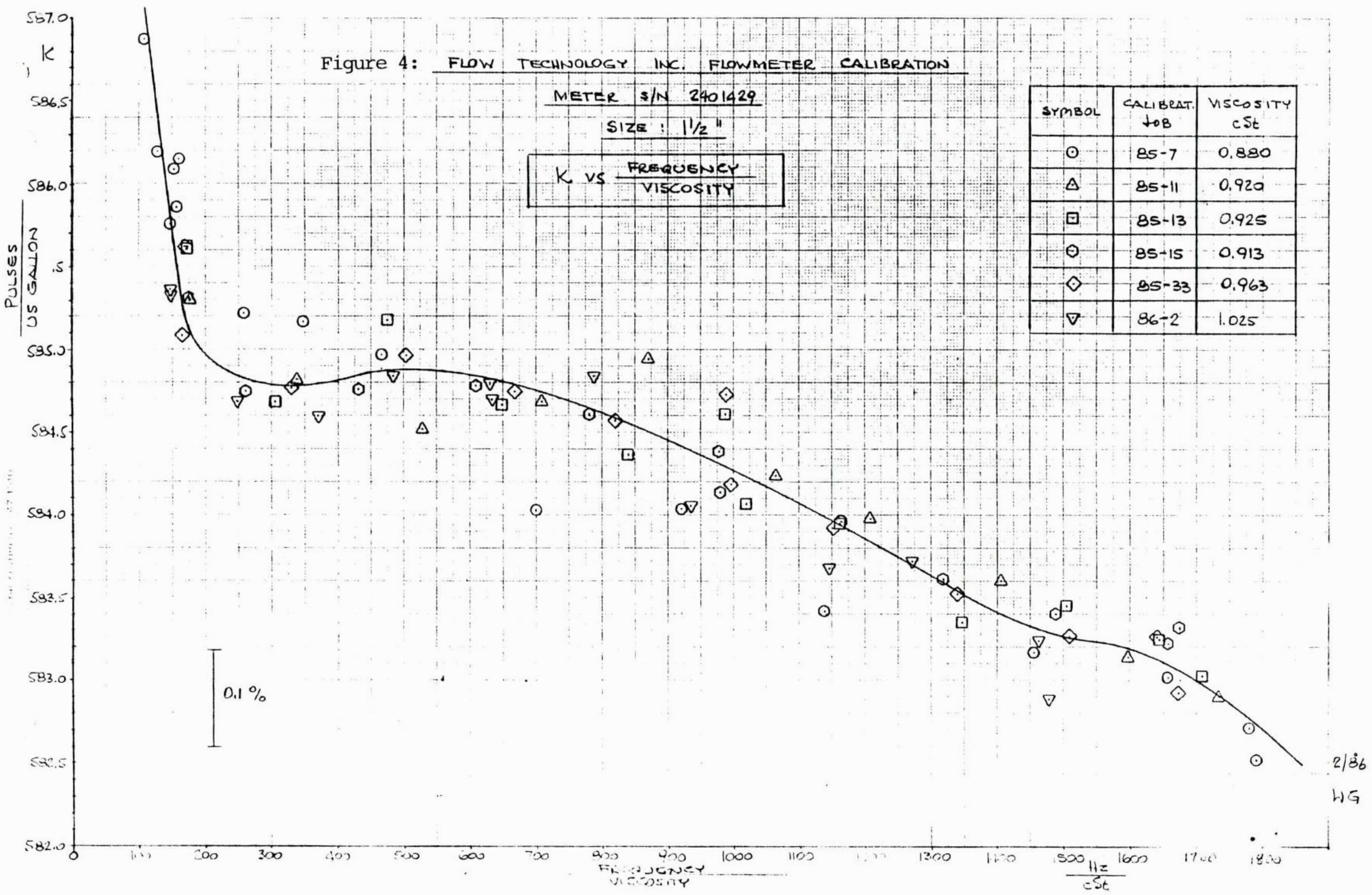


Figure 4: FLOW TECHNOLOGY INC. FLOWMETER CALIBRATION

METER S/N 2401429

SIZE : 1½"

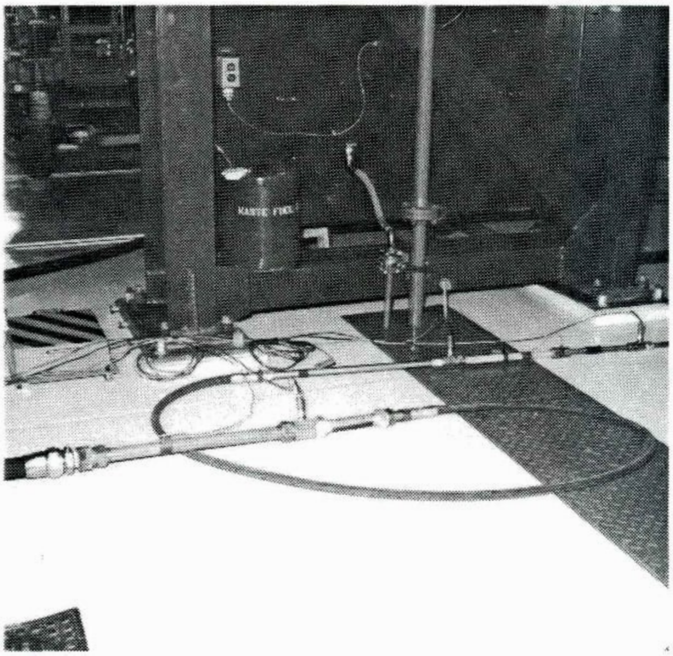


Figure 5: NRCC Fuel Flowmeters Installed for Test Series 10-X

Table 1a: NRCC Data, Series 10-X

TEST POINT	FREQUENCY - Hz			FUEL TEMP. °C		VISCOSITY -cSt		C_{EX}	C_{CR}*	SG_{TF}		C_T
	¾"	1"	1½"	¾" & 1"	1½"	¾" & 1"	1½"	$\times 10^{-4}$	$\times 10^{-5}$	¾" & 1"	1½"	
10-0	965	520	129	24.7/24.1	24.0	0.875	0.875	5.8	6.134	0.7532	0.7532	0.99999
10-1	147	80.5	19.5	18.9/18.9	18.8	0.91	0.91		≃0	0.7572	0.7572	≃1.0
10-2	288.5	156	39	18.4/18.4	18.4	0.92	0.92			0.7576	0.7576	
10-3	426.5	230	57.5	19.5/19.5	19.5	0.905	0.905			0.7568	0.7568	
10-4	594	320	80	20.6/20.6	20.6	0.90	0.90			0.7559	0.7559	
10-5	710	383.5	96	20.0/20.1	19.9	0.905	0.905			0.7564	0.7564	
10-6	870.5	468	116	19.2/19.1	19.0	0.91	0.91			0.7571	0.7571	
10-7	1012	544.5	134	17.7/17.7	17.5	0.93	0.93			0.7582	0.7582	
10-8	1140	614.5	152.5	16.3/16.2	16.0	0.94	0.94			0.7594	0.7594	
10-9	1220.5	656.5	163	14.8/14.8	14.6	0.955	0.955			0.7606	0.7606	

$SG_{15.56/15.56^\circ C} = 0.7599$

* See Appendix A

Table 1b: NRCC Data, Series 10-X

TEST POINT	FREQUENCY/VISCOSITY			K – PULSES / US GALLON			W_F – lbm/h				ΔWF_{MAX}	
	¾"	1"	1½"	¾"	1"	1½"	¾"	1"	1½"	AVE.	lbm/h	%
10-0	1103	594	147	4380.0	2355.5	585.8	4981	4990	4978	4983	12	0.24
10-1	161	88	21	4358.4	-	-	766	-	-	766	-	-
10-2	313	170	42	4367.0	2361.7	-	1502	1502	-	1502	0	0
10-3	471	254	63	4377.6	2355.8	-	2213	2218	-	2215	5	0.22
10-4	660	355	89	4381.2	2354.5	-	3076	3083	-	3080	7	0.23
10-5	785	424	106	4381.4	2354.6	-	3679	3698	-	3689	19	0.51
10-6	956	514	127	4380.8	2355.1	586.45	4515	4515	4495	4508	20	0.44
10-7	1088	585	144	4380.0	2355.5	585.86	5258	5260	5205	5241	55	1.05
10-8	1213	654	162	4379.2	2355.8	585.36	5933	5945	5938	5939	12	0.20
10-9	1278	687	171	4378.6	2355.9	585.18	6363	6361	6359	6361	4	0.06

Table 2: ETF Data & Comparison, Series 10-X

TEST POINT	WF READING*		WF, SG = .76, lbm/h			ΔWF_{ETF}	WF_{ETF}	WF_{NRC}**	$\Delta WF_{NRC-ETF}$		$\frac{\Delta WF_{ETF}}{WF_{ETF AVE.}}$
	LOW	HIGH	LOW	HIGH	AVE.	HI-LO	AVE. OF AVERAGES	lbm/h	lbm/h	%	%
10-1	999	1014	759	771	765	12	765	766	1	0.13	1.57
10-2	1948	1998	1480	1518	1499	38					2.53
	1933	2005	1469	1524	1496	55	1498	1502	4	0.27	3.68
10-3	2897	2947	2202	2240	2221	38	2221	2215	-6	-0.27	1.71
10-4	4036	4091	3067	3109	3088	42					1.36
	4106	4136	3121	3143	3132	22					0.70
	4071	4116	3094	3128	3111	34	3110	3080	-30	-0.97	1.09
10-5	4846	4906	3683	3729	3706	46					1.24
	4911	4951	3732	3763	3748	31					0.83
	4921	4956	3740	3767	3753	27	3736	3689	-47	-1.27	0.72
10-6	5985	6055	4549	4602	4575	53					1.16
	5980	6015	4545	4571	4558	26	4566	4515	-51	-1.13	0.57
10-7	7019	7109	5334	5403	5369	69					1.28
	6949	7009	5281	5327	5304	46	5336	5259	-77	-1.46	0.87
10-8	7973	8053	6059	6120	6090	61	6090	5939	-151	-2.54	1.00
10-9	8553	8623	6500	6553	6527	53	6527	6362	-165	-2.59	0.81

* SG SETTING = 1.0
** AVERAGE OF $\frac{3}{4}$" & 1" METERS ONLY

Table 3: NRCC Data, Series 11-X

TEST POINT	FREQUENCY Hz	T_{FUEL} °C	VISCOSITY cSt	C_{EX}	SG_{TF}	$\frac{\text{FREQUENCY}}{\text{VISCOSITY}}$	K $\frac{\text{PULSES}}{\text{US GALLON}}$	WF lbm/h
11-1	171.5	19.2	0.910	5.8×10^{-4}	0.7570	188	585.03	6660
11-2	182.5	17.8	0.920		0.7581	198	584.98	7098
11-3	198	15.5	0.945		0.7599	209	584.94	7720
11-4	216	13.2	0.965		0.7618	224	584.89	8444
11-5	235.5	12.3	0.970		0.7625	243	584.85	9215
11-6	257	12.0	0.975		0.7627	264	584.82	10060
11-7	278.5	11.5	0.980		0.7631	290	584.79	10907
11-8	303	10.6	0.990		0.7638	306	584.78	11878
11-9	324.5	9.9	0.990		0.7644	328	584.78	12731
11-10	339	9.5	1.00		0.7647	339	584.78	13305
11-11	358	9.0	1.01		0.7651	354	584.78	14058
11-12	371	8.6	1.01		0.7654	367	584.79	14574
11-13	398	8.4	1.015		0.7656	392	584.80	15639
11-14	418	8.0	1.015		0.7659	412	584.83	16430
11-15	444.5	7.8	1.02		0.7661	436	584.85	17476
11-16	473.5	7.7	1.02		0.7661	464	584.87	18615
11-17	494	7.6	1.02		0.7662	484	584.88	19423
11-18	520	7.5	1.02		0.7663	510	584.88	20448
11-19	536.5	7.3	1.02		0.7665	526	584.88	21102
11-20	558.5	7.4	1.02		0.7664	547	584.88	21965
11-21	574.5	7.5	1.02		0.7663	563	584.86	22592
11-22	717.5	7.6	1.02		0.7662	703	584.75	28217

$SG_{15.56/15.56} = 0.7599$ $C_{CR} \approx 0$ $CT = 1.0$

Table 4: ETF Data & Comparison, Series 11-X

TEST POINT	WF READING*		WF, SG = .76, lbm/h			ΔWF_{ETF}	WF_{NRC}	ΔWF NRC-ETF		$\frac{\Delta WF_{ETF}}{WF_{ETF\,AVE.}}$	
	LOW	HIGH	LOW	HIGH	AVE.	lbm/h	lbm/h	lbm/h	%	%	
11-1	8698	9018	6610	6854	6732	244	6660	-72	-1.08	3.62	doubtful point
11-2	9282	9342	7054	7100	7077	46	7098	21	0.30	0.65	
11-3	10067	10147	7651	7712	7681	61	7720	39	0.51	0.79	
11-4	10946	11136	8319	8463	8391	144	8444	53	0.63	1.72	
11-5	11985	12175	9109	9253	9181	144	9215	34	0.37	1.57	
11-6	13089	13204	9948	10035	9991	87	10060	69	0.69	0.87	
11-7	14144	14313	10749	10878	10813	129	10907	94	0.86	1.19	
11-8	15378	15537	11687	11808	11748	121	11878	130	1.09	1.03	
11-9	16472	16677	12519	12674	12596	155	12731	135	1.06	1.23	
11-10	17246	17446	13107	13259	13183	152	13305	122	0.92	1.15	
11-11	18220	18400	13847	13984	13915	137	14058	143	1.02	0.98	
11-12	18885	19050	14353	14478	14415	125	14574	159	1.09	0.87	
11-13	20314	20449	15439	15541	15490	102	15639	149	0.95	0.66	
11-14	21293	21463	16183	16312	16247	129	16430	183	1.11	0.79	
11-15	22667	22837	17227	17356	17292	129	17476	184	1.05	0.75	
11-16	24106	24256	18321	18435	18378	114	18615	237	1.27	0.62	
11-17	25165	25345	19125	19262	19194	137	19423	229	1.18	0.71	
11-18	26404	26609	20067	20223	20145	156	20448	303	1.48	0.77	
11-19	27293	27548	20743	20936	20840	193	21102	262	1.24	0.93	
11-20	28358	28632	21552	21760	21656	208	21965	309	1.41	0.96	
11-21	29302	29482	22269	22406	22338	137	22592	254	1.12	0.61	
11-22	36576	36766	27798	27942	27870	144	28217	347	1.23	0.52	

* SG SETTING = 1.0

5 & 6 March 1986

Table 5a: NRCC Data, Series 13-X

TEST POINT	FREQUENCY - Hz						FUEL TEMPERATURE °C			VISCOSITY - cSt		
	¾"		1"		1½"							
	LOW	HIGH	LOW	HIGH	LOW	HIGH	¾"	1"	1½"	¾"	1"	1½"
13-1	-	124.5	-	68	-	18	35.7	36.3	15.1	0.79	0.79	0.95
13-2	1575	1578	849	850	211	211	30.1	30.3	20.4	0.83	0.83	0.90
13-3	1591	1596	858	862	212	213	27.4	27.6	17.5	0.85	0.85	0.925
13-4	1577	1581	848	851	748	749	15.3	15.4	8.8	0.95	0.95	1.00
13-5	1596	1600	860	862	295	296	19.8	19.9	11.2	0.90	0.90	0.98
13-6	1591	1595	853	854	389	391	18.3	18.4	10.5	0.92	0.92	0.99
13-7	1584	1589	853	856	494	495	16.9	17.0	9.7	0.93	0.93	0.995
13-8	1578	1582	848	852	613	614	15.8	16.0	9.1	0.94	0.94	1.00
13-9	1575	1577	847	849	699	700	15.2	15.3	8.7	0.95	0.95	1.00
13-10	1573	1576	847	848	746	747	15.1	15.2	8.65	0.95	0.95	1.00
13-11	126	127	68	69	17	17	39.5	40.0	15.1	0.77	0.77	0.95
13-12	325	326	174	175	42	43	34.9	35.2	18.2	0.79	0.79	0.925
13-13	508	510	273	274	67	68	34.6	35.0	21.0	0.79	0.79	0.895
13-14	720	725	388	389	96	96	32.6	32.9	20.4	0.81	0.81	0.90
13-15	903	906	484	488	120	120	30.2	30.5	19.0	0.83	0.83	0.91
13-16	1112	1117	599	601	148	149	27.4	27.6	16.7	0.85	0.85	0.925
13-17	1320	1323	709	712	175	176	25.3	25.5	15.1	0.865	0.865	0.95
13-18	1479	1484	796	798	197	198	23.8	24.0	13.9	0.875	0.875	0.955
13-19	1585	1590	853	857	211	212	22.5	22.7	12.7	0.885	0.885	0.97

5 & 6 March 1986

Table 5b: NRCC Data, Series 13-X

TEST POINT	SG_{TF}			FREQUENCY/VISCOSITY (AVE.)			K (AVE.) $\frac{\text{PULSES}}{\text{US GALLON}}$		
	¾"	1"	1½"	¾"	1"	1½"	¾"	1"	1½"
13-1	.7439	.7434	.7603	157	86	19	4359.6	-	-
13-2	.7484	.7482	.7561	213	1024	234	4356.4	2354.7	584.87
13-3	.7505	.7503	.7584	1875	1012	230	4372.5	2354.9	584.88
13-4	.7601	.7600	.7653	1662	894	749	4375.0	2355.9	584.69
13-5	.7565	.7565	.7634	1775	957	301	4373.7	2355.5	584.78
13-6	.7577	.7576	.7639	1731	928	394	4374.2	2355.7	584.81
13-7	.7588	.7588	.7645	1706	919	497	4374.5	2355.8	584.88
13-8	.7597	.7596	.7650	1681	904	614	4374.7	2355.9	584.84
13-9	.7602	.7601	.7653	1659	893	700	4375.0	2356.0	584.76
13-10	.7602	.7602	.7654	1657	892	747	4375.0	2356.0	584.70
13-11	.7407	.7407	.7602	164	89	18	4357.7	-	-
13-12	.7446	.7443	.7578	412	221	46	4374.8	2357.0	-
13-13	.7448	.7445	.7556	644	346	75	4381.0	2354.5	-
13-14	.7464	.7461	.7561	892	480	107	4381.1	2354.9	-
13-15	.7483	.7480	.7572	1090	585	132	4380.0	2355.5	586.30
13-16	.7505	.7505	.7590	1311	706	160	4378.4	2356.0	585.40
13-17	.7522	.7522	.7603	1528	821	185	4376.3	2356.2	585.04
13-18	.7533	.7533	.7612	1693	911	207	4374.6	2355.8	584.94
13-19	.7543	.7543	.7622	1794	966	218	4373.4	2355.4	584.91

$SG_{15.56/15.56} = 0.7599$

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Table 5c: NRCC Data, Series 13-X

TEST POINT	FUEL FLOW lbm/h									CORE OR TOTAL AVERAGE	ΔW_F OF AVERAGES	ΔW_F OF AVERAGES
	$\frac{3}{4}$"			1"			$1\frac{1}{2}$"					
	LOW	HIGH	AVE.	LOW	HIGH	AVE.	LOW	HIGH	AVE.	lbm/h	lbm/h	%
13-1	-	-	638	-	-	-	-	-	-	638	-	-
13-2	8121	8136	8129	8097	8106	8101	8187	8187	8187	8139	86	1.06
13-3	8196	8222	8209	8205	8243	8224	8251	8290	8270	8234	81	0.98
13-4	8223	8244	8233	8210	8240	8225	29385	29424	29404	8229[c]	8	0.10
13-5	8285	8306	8295	8290	8309	8300	11558	11598	11578	8297[c]	5	0.06
13-6	8272	8292	8282	8233	8243	8238	15251	15329	15290	8260[c]	44	0.53
13-7	8247	8273	8260	8246	8275	8260	19380	19419	19400	8260[c]	0	0
13-8	8225	8245	8235	8206	8245	8225	24066	24105	24085	8230[c]	10	0.12
13-9	8214	8224	8219	8202	8221	8211	27457	27496	27476	8215[c]	8	0.10
13-10	8203	8219	8211	8203	8212	8207	29310	29349	29330	8209[c]	4	0.05
13-11	643	648	645	-	-	-	-	-	-	645	-	-
13-12	1660	1665	1663	1649	1659	1654	-	-	-	1658[c]	9	0.54
13-13	2592	2602	2597	2591	2600	2595	-	-	-	2596[c]	2	0.08
13-14	3682	3707	3694	3690	3699	3695	-	-	-	3695[c]	1	0.03
13-15	4630	4646	4638	4613	4651	4632	4651	4651	4651	4640	19	0.41
13-16	5721	5747	5734	5727	5746	5736	5759	5798	5778	5749	44	0.76
13-17	6810	6825	6818	6793	6822	6808	6826	6865	6845	6824	37	0.54
13-18	7644	7670	7657	7639	7659	7649	7694	7733	7713	7673	64	0.83
13-19	8205	8231	8218	8199	8237	8218	8252	8292	8272	8236	54	0.66

[c] AVERAGE OF CORE FLOW ONLY

Table 6a: ETF Data & Comparison, Series 13-X

TEST POINT	WF READING*		WF, SG = .76, lbm/h			ΔWF_{ETF}	WF_{NRC}**	ΔWF NRC-ETF		$\frac{\Delta WF_{ETF}}{WF_{ETF\,AVE.}}$
	LOW	HIGH	LOW	HIGH	AVE.	lbm/h	lbm/h	lbm/h	%	%
13-1	1119	5036	850	3827	2338	2977	-	-	-	127
13-2	6140	15707	4666	11937	8301	7271	8187	-114	-1.39	88
13-3	6499	15268	4939	11604	8271	6665	8270	-1	-0.01	81
13-4	37171	39054	28250	29681	28965	1431	29404	439	1.49	5
13-5	13124	17836	9974	13555	11765	3581	11578	-187	-1.62	30
13-6	16712	23316	12701	17720	15210	5019	15290	80	0.52	33
13-7	22507	28033	17105	21305	19205	4200	19400	195	1.01	22
13-8	29441	33044	22375	25113	23744	2738	24085	341	1.42	11
	29891	32669	22717	24828	23772	2111	24085	313	1.30	9
13-9	34513	36716	26230	27904	27067	1674	27476	409	1.49	6
13-10	36876	39659	28026	30141	29083	2115	29330	247	0.84	7

* FACILITY SYSTEM - SG SETTING = 1. 0

** 1½" FLOWMETER

Table 6b: ETF Data & Comparison, Series 13-X

TEST POINT	WF_{CORE} lbm/h			ΔWF_{CORE}	WF_{NRC}**	ΔWF NRC-ETF/CORE		$\frac{\Delta WF_{CORE}}{WF_{CORE_{AVE.}}}$
	LOW	HIGH	AVE.	lbm/h	lbm/h	lbm/h	%	%
13-1	608	622	615	14	642	27	4.21	2.28
13-2	7968	8049	8008	81	8115	7	0.09	1.01
13-3	8010	8174	8092	164	8216	124	1.52	2.03
13-4	8159	8183	8171	24	8229	58	0.70	0.29
13-5	8223	8238	8230	15	8297	67	0.81	0.18
13-6	8179	8212	8195	33	8260	65	0.79	0.40
13-7	8180	8203	8192	23	8260	68	0.82	0.28
13-8	8148	8164	8156	16	8230	74	0.90	0.20
13-9	8138	8159	8148	21	8215	67	0.82	0.26
13-10	8127	8139	8133	12	8209	76	0.93	0.15
13-11	621	623	622	2	645	23	3.57	0.32
13-13	2536	2543	2540	7	2596	56	2.16	0.28
13-14	3609	3620	3614	11	3695	81	2.19	0.30
13-15	4530	4568	4549	38	4635	86	1.86	0.84
13-16	5619	5642	5630	23	5735	105	1.83	0.41
13-17	6722	6747	6734	25	6813	79	1.16	0.37
13-18	7598	7634	7616	36	7653	37	0.48	0.47
13-19	8109	8139	8124	30	8218	-6	-0.07	0.37

* ENGINE CORE FLOW FROM MASS FLOWMETER
** AVERAGE OF $\frac{3}{4}$" & 1" FLOWMETERS

APPENDIX A

SPECIFIC GRAVITY OF AVIATION TURBINE FUELS AS A FUNCTION OF TEMPERATURE

A revision of the method used by the Engine Laboratory for calculating the specific gravity of aviation fuels, as a function of temperature, revealed that different agencies used varying equations which yielded slightly different values.

In consultation with the Fuels and Lubricants Laboratory, NRC, a thermal expansion relationship was accepted, based on work by Barnett and Hibbard and by Chin and Lefebvre (Refs. 4 and 5).

$$SG_T = SG_{288.71\ K}\left[1 - 1.8\ C_{EX}(T_F - 288.71) - 0.090\frac{(T_F - 288.71)^2}{(T_{CR} - 288.71)^2}\right]$$

where

SG_T = specific gravity of the fuel at temperature T

C_{EX} = coefficient of thermal expansion of fuel, $\frac{1}{°F}$

A plot of C_{EX} versus SG 60/60°F is given in Figure 6, and a polynominal curve fit is given in Table 7.

T_F = temperature of the fuel at the point of flow measurement, K.

T_{CR} = critical temperature of the fuel, K, see Table 8.

For temperatures close to standard, i.e. 60°F or 15.56°C, the last term inside the bracket approaches zero and may be neglected.

For ease of computation let:

$$C_{CR} = 0.090\frac{(T_F - 288.71)^2}{(T_{CR} - 288.71)^2}$$

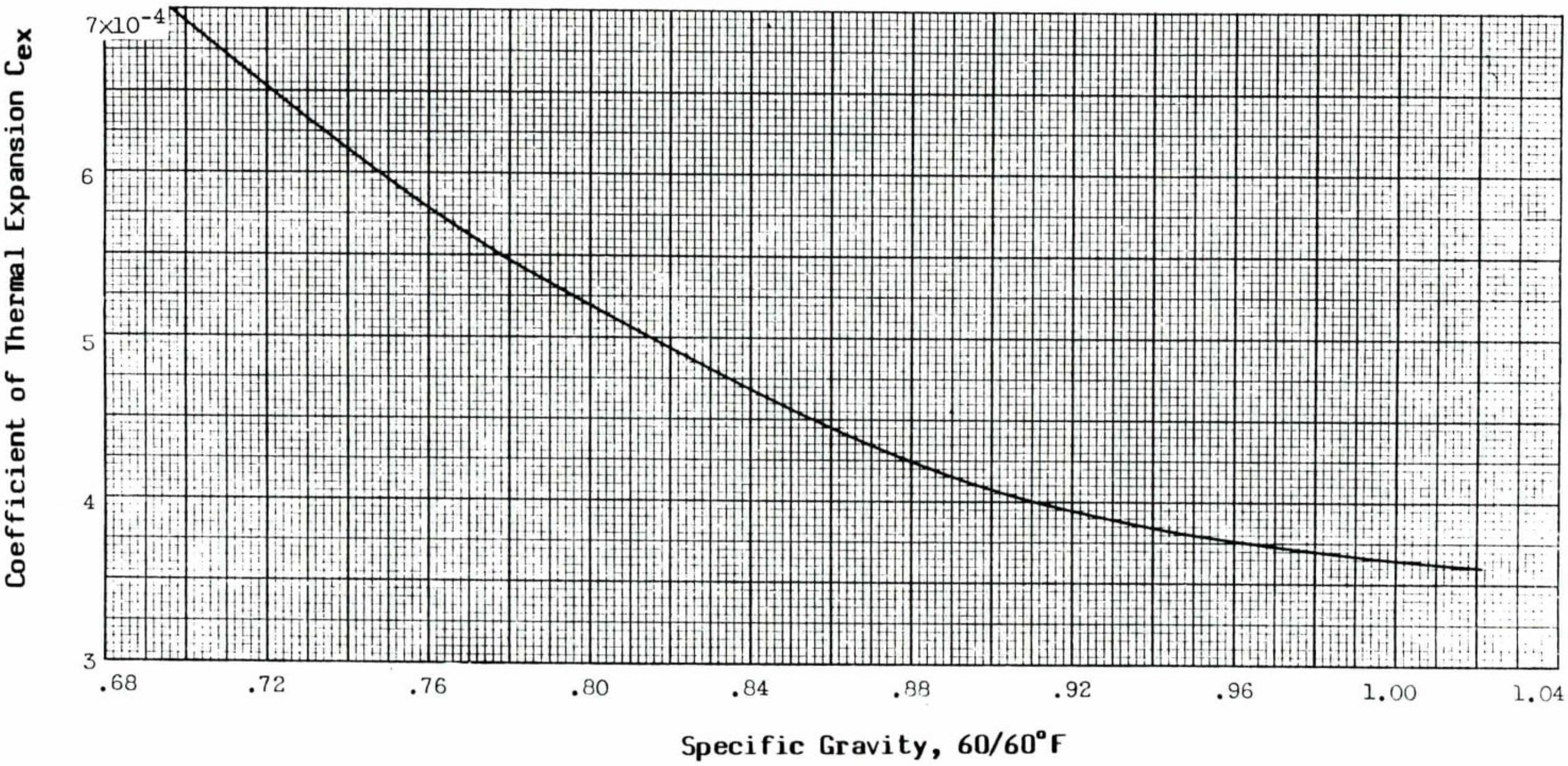

Figure 6: Coefficients of Thermal Expansion for Fuels of Different 60°F Specific Gravities

TABLE 7: EQUATION FOR COEFFICIENTS OF THERMAL EXPANSION FOR FUELS OF DIFFERENT 60°F SPECIFIC GRAVITIES

(FROM REF. 4 UNLESS NOTED)

$SG_{60/60°F}$	$C_{ex_{curve}}$	$C_{ex_{calc.}}$	
0.70	6.93	6.929	R2 = 0.999796 a = 52.3575 b = -123.3954 c = 104.7496 d = -30.2584
0.72	6.53	6.521	
0.73	6.33	6.329	
0.74	6.15	6.144	
0.75	5.96	5.967	
0.76	5.78	5.798	$C_{ex} = 52.3575$ $- 123.3954 (SG_{60/60})$ $+ 104.7496 (SG_{60/60})^2$ $- 30.2584 (SG_{60/60})^3$
0.77	5.62	5.635	
0.78	5.47	5.480	
0.79	5.33	5.331	
0.80	5.20	5.189	
0.81	5.07	5.053	
0.82	4.94	4.923	
0.83	4.81	4.800	
0.84	4.69	4.682	
0.85	4.57	4.571	
0.86	4.45	4.464	
0.88	4.25	4.267	
0.90	4.075	4.090	
0.92	3.95	3.932	

TABLE 8: SOME THERMOPHYSICAL PROPERTIES

(FROM REF. 5 UNLESS NOTED)

	JP4	JP5	JET-A1
T_{cr}, K	612.0	684.8	587*
DENSITY, $\frac{kg}{m^3}$	773	827	807**
C_{ex}, °F^{-1}	0.000557	0.000485	0.000507***

* From O. Gulder, Fuels & Lubricants Laboratory
** Mean of specification limits
*** From Figure 6.

APPENDIX B

DERIVATION OF VOLUME - MASS CONVERSION FACTOR

It has been found that users of turbine flowmeters are employing slightly differing numerical values for conversion from volume to mass.

Careful examination has yielded the derivation below:

$$1 \text{ US gallon} = \cancel{1 \text{ US gallon}} * 62.3663 \left[\frac{\text{lbm}_{H2O},\ 15.56°\text{C}}{\cancel{\text{ft}^3}}\right] * 0.133680555 \left[\frac{\cancel{\text{ft}^3}}{\cancel{\text{US gallon}}}\right] =$$

$$1 \text{ US gallon} = 8.337162 \left[\text{lbm}_{H2O},\ 15.56°\text{C}\right]$$

The specific gravity of a liquid, at temperature T; is defined as:

$$SG_T = \frac{\text{Density of liquid at temperature T}}{\text{Density of water at 15.56°C}}$$

<u>NOTE</u>: 15.56°C = 60°F

The density can be expressed in either kg/m^3 or kg/ℓ, without introducing a significant error.

$$SG_T = \frac{(\text{kg}_{\text{fuel}},\ T_{\text{fuel}}) * \ell}{\ell * (\text{kg}_{H2O},\ 15.56°\text{C})}$$

which can also be written for convenience as:

$$SG_T = \frac{(\mathrm{lbm}_{fuel},\ T_{fuel}) * \ell}{\ell * (\mathrm{lbm}_{H2O},\ 15.56^\circ C)}$$

Hence,

$$1 \text{ US gallon} = 8.337162 \left[\cancel{\mathrm{lbm}_{H2O},\ 15.56^\circ C} \right] * SG_T \left[\frac{(\mathrm{lbm}_{fuel},\ T_{fuel}) * \cancel{\ell}}{\cancel{\ell} * \cancel{(\mathrm{lbm}_{H2O},\ 15.56^\circ C)}} \right]$$

$$1 \text{ US gallon} = 8.337162 * SG_T \left[\mathrm{lbm}_{fuel},\ T_{fuel} \right]$$

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SUMMARY/SOMMAIRE

15 Describes the calibration check of fuel flow measuring system at CFB Baden-Soellingen. Excessive flow fluctuations indications precluded calibration. Recommendations made for some system improvement.

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