Fuel Flow Metering for Fishing Vessels

Phase III Report: Fuel meter testing on a diesel engine

The Sea Fish Industry Authority

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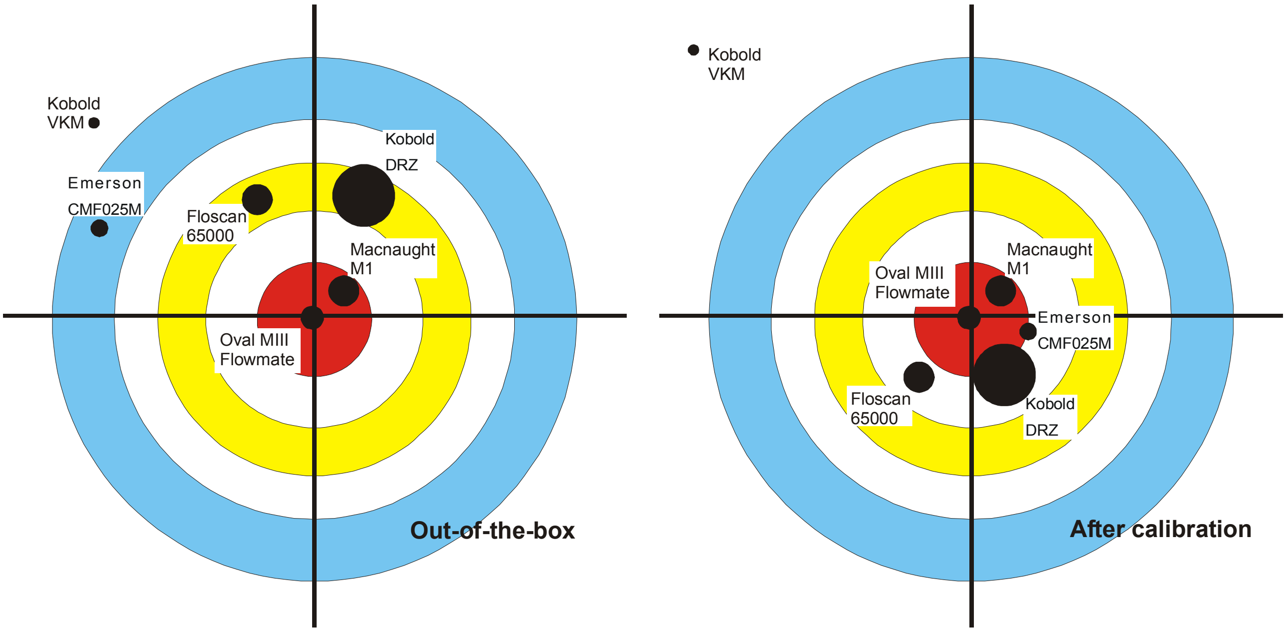
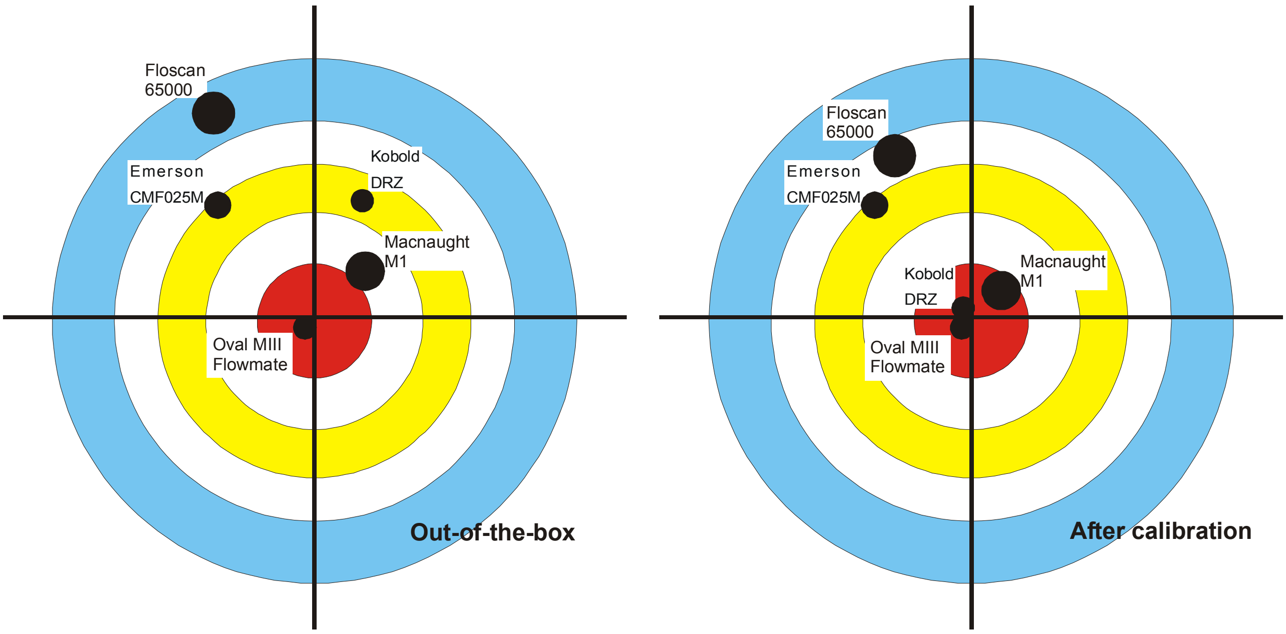
Executive Summary

PHASE II : TESTING UNDER LABORATORY CONDITIONS



PHASE III : TESTING ON ENGINE



The ‘target analogy’ introduced in the Phase II report is revisited to graphically indicate the relative performance of the fuel flow measurement systems incorporating the flow meters under investigation. On the targets, the distance of the centre of the circle for a given meter represents the accuracy of the device, the size of the circle represents the repeatability of observations. The LHS target shows the relative situation before calibration of the devices, the RHS target shows the same, after calibration. The upper targets reflect the Phase II investigations, the lower targets reflect the Phase III investigations.

The lower RHS target of the diagram (also Figure 29) illustrates that it is possible to use three of the five meters subjected to testing in Phase III in an effective fuel metering role for the CSM Engine Dynamometer test cell engine. It is believed that the full scale flow rating of the Emerson CMF025M used with a turn down ratio of 50 would make it unsuitable for fuel metering on the CSM Engine Dynamometer test cell engine. The reason for the poor performance of the Floscan fuel meter is unknown.

At the end of Phase II of the overall study, it was stated that the essential distinction between the fuel meters and their measurement systems reduced to considerations of the ease of undertaking a calibration exercise on a working fishing vessel. According to the Phase III results, the Oval MIII Flowmate device is likely to produce valid observations of fuel flow without requiring calibration *in situ*. For this reason, it is our favoured fuel meter.

The objective for the Phase III work, stated at the end of the Phase II report was stated as needing to investigate whether the relative rank of any particular sensing device changes when the meter is installed on an engine and subjected to, for example, vibration and pulsating flows. The following listing addresses this objective:

Device	**Change when operating on a working engine**
Oval MIII Flowmate	Slightly lower accuracy and repeatability
Macnaught M1	Slightly lower accuracy and repeatability
Kobold DRZ	Much improved accuracy and precision
Emerson CMF025M	Slightly lower repeatability, lower accuracy
Floscan Cruisemaster 65000	Lower repeatability and lower accuracy

In making this assessment, we have used figures for accuracy applying after calibration of the sensors has been undertaken.

Erratum

In the original release of this document, in certain locations in the text and diagrams the Oval MIII Flowmate fuel meter was referred to as the “Flowtech Oval MIII”. This was an error for which the authors apologise. The relevant entries and diagrams have been updated to reflect the correct text in this document which is “Oval MIII Flowmate”.

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Introduction

During phase I research the team conducted a review of diesel injection engines, fluid flow metering theory and available fluid flow transducers, highlighting a number of factors that should be considered when selecting a fuel flow metering solution for use in the field - aboard small to medium sized commercial fishing vessels. A number of devices were chosen that represent a sample of various transducer types, suited to the application (see Table 1). The selection covers gear and piston positive displacement, variable aperture, inferential and coriolis mass flow meters.

The purpose of phase II testing was to assess the performance of the meters under controlled laboratory conditions. Flow tests were performed across the full-scale range of each device, with a view to assessing their performance in terms of accuracy and precision. The results of Phase II excluded the use of the Kobold VKM variable aperture meter in Phase III, due to stiction issues, and found oval gear type flow meters to be the most accurate “out of the box” and after calibration.

Phase III now reports on tests indicating the performance of the flow transducers when installed within the fuel lines of a running engine.

The Engine Test Cell

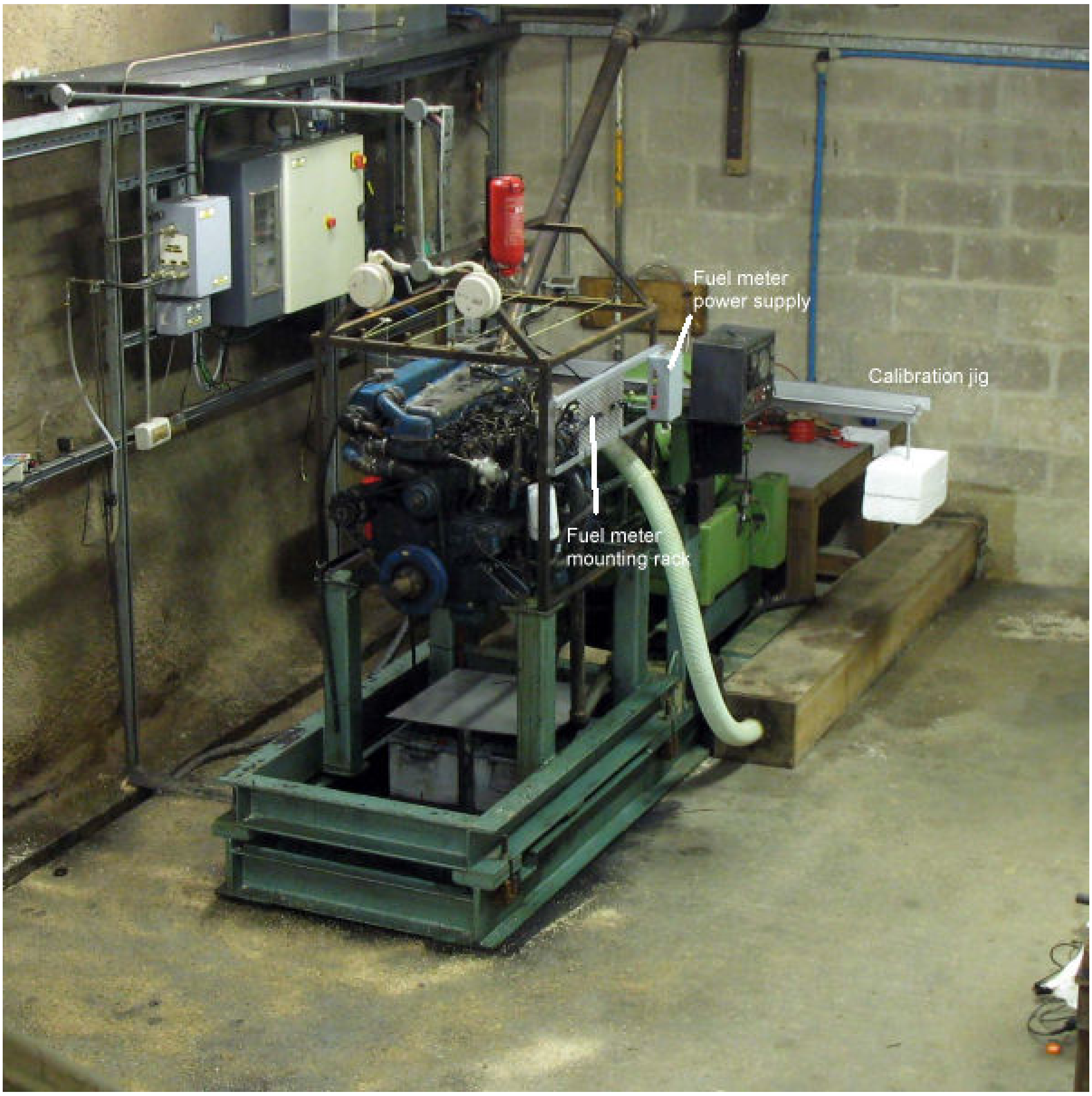


Figure 1: Perkins 6354 Engine Test Cell (Calibration arm pictured on dynamometer)

Installation of fuel meters

In order to evaluate the performance of the fuel flow meters when metering an engine supply, they were installed within the fuel line of a Perkins 6354 90kW diesel engine. This engine has been used in the past by the University of Exeter to evaluate various potential fuel-saving technologies for SeaFISH. The CP engineering CADET 3099 SCADA system that the engine and the driven Schenck W230 Dynamometer are controlled by, has been programmed with a number of engine speed/load “test points” that correspond to stages in a trawler excursion.

The engine was run at these set points while the fuel consumed was logged by a CP Engineering FMS 1000 fuel weigher. The SCADA system was modified such that simultaneous logging of the fuel consumed as indicated by the meter under test could be undertaken.

Before testing began, the return line was broken to examine the proportion of return flow. The only flow returned was leakage from the injectors, and was essentially unmeasurable, so it was decided to close the return line and measure only the delivered fuel. This simplified the scope of the practical investigation; it is known that conditions for the return fuel are far more variable than for the fuel feed line for engine where the return flow is appreciable, for example, there can be greater pulsations in the flow, higher proportions of entrained air and altered temperatures.

To facilitate fast switchover of fuel meters tested, a fuel meter mounting rack was prepared and fixed to the fire control support frame around the engine. A break-out box was mounted on this that relayed signals back to a remote terminal unit (RTU, as detailed in the Phase II report and outlined below) so that signal processing methods were consistent between the Phase II and Phase III work. The fuel feed line was broken after the lift pump, routed by hose to the mounting rack to the meter under test and then back to the engine fuel filter.

The decision to install the meters under test at this location was made because of the presence of another fuel filter on the fuel line before the lift pump, so particulates were not of concern. Proximity to the engine fuel filter would allow easy bleeding of the fuel system after each meter change.

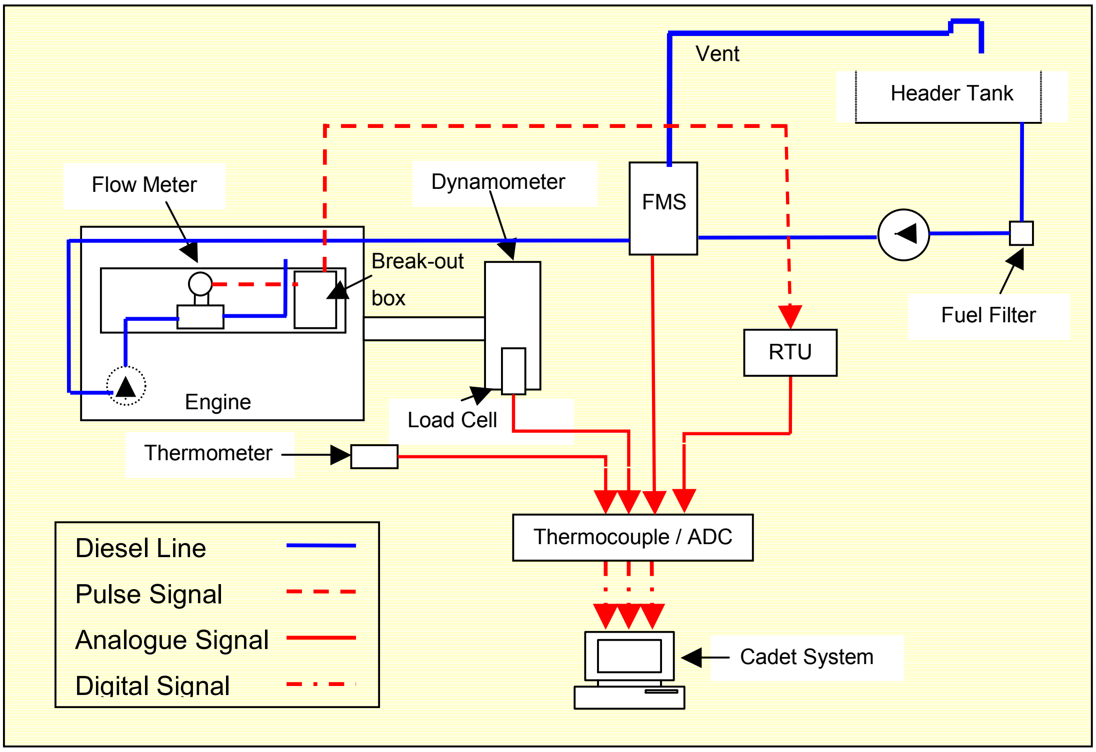


Figure 2) Engine test facility schematic

Data acquisition system

The engine and dynamometer test facility is built around a Cadet 3099 Supervisory Control and Data Acquisition (SCADA) system, provided by CP Engineering. This provides a minimum update frequency of 10Hz on each channel, and provides a corresponding timestamp resolved to 0.1s when the channel is logged.

The SCADA system was extended to meet the requirements of flow meter testing by the addition of two analogue signal inputs for the flow-rate transducers. The channels are recorded at up to 16 bit resolution, over user-selectable voltage ranges. Generally, a voltage range of –0.25V to 10.25V was selected for logging the indicated flow rates from the meters under test.

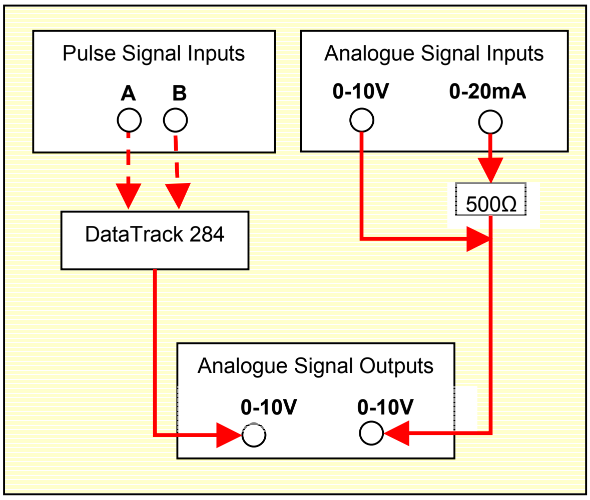
As various transducer types produce different kinds of output signal (i.e. voltage output, current output, pulse count output or frequency output) a Remote Terminal Unit (RTU) was constructed that converted all of the possible transducer outputs types into 0-10V analogue voltage signals.

The RTU is built around a DataTrack 284, dual-channel, panel mount indicator that can accept pulse, time to live, relay contact and encoder signals (~ cost: £330 + VAT). It also provides one analogue output, which was routed into the CP SCADA system. In the case that the output signal of the meter under test was a pulse output, the DataTrack 284 was used to convert this to an analogue voltage output, corresponding to pulse frequency. In the case that the output signal of the meter under test was a current in the range 4-20mA, this was passed through a 500 Ω precision resistor. In the case that the output signal of the meter under test was a voltage output in the range 0-10V, this was patched straight through the RTU to the latter's analogue output channel.

The RTU can be fully programmed via RS-485 communication.

The meters under test also had varying power requirements. Consequently, the RTU was additionally constructed to provide local connection points for regulated transducer excitation voltages of 10V, 12V and 24V, for convenience in testing.

(a)



(b)

Figure 3: a) Remote Terminal Unit b) Remote Terminal Unit Schematic Diagram

CP Engineering FMS 1000 Fuel weigher

The FMS-1000 Gravimetric Fuel Measuring System is a compact, high precision instrument for measuring specific fuel consumption of diesel and petrol engines developing up to 1000 kW. The fuel weigher uses a 20N load cell to measure consumed fuel. It also cancels any vibration mechanically, as the construction is stiff and has no moving parts. The fuel cell has a mass capacity of ~1 kg, is mounted on top of the 20N load cell and has four fuel ports all connected by lightweight bellows. These ports are for: fuel feed, fuel supply, fuel return and vent.

The FMS1000 system employed is relatively simple in concept and operation. The system functions by dosing approximately 1 kg of fuel into a vessel that is in the fuel delivery line between the header tank and the engine. Return fuel from the engine is also delivered to this weighing vessel. When the predefined fill level is achieved, the fuel delivery from the header tank to this vessel is suspended. The vessel sits upon a load cell and the mass of the vessel is logged at predefined time intervals to derive the mass fuel consumption. When a predefined lower level of fuel is achieved, data logging is suspended and the vessel is re-filled. The operation of the FMS is controlled by the SCADA system software but has hardware settings that intervene when appropriate.

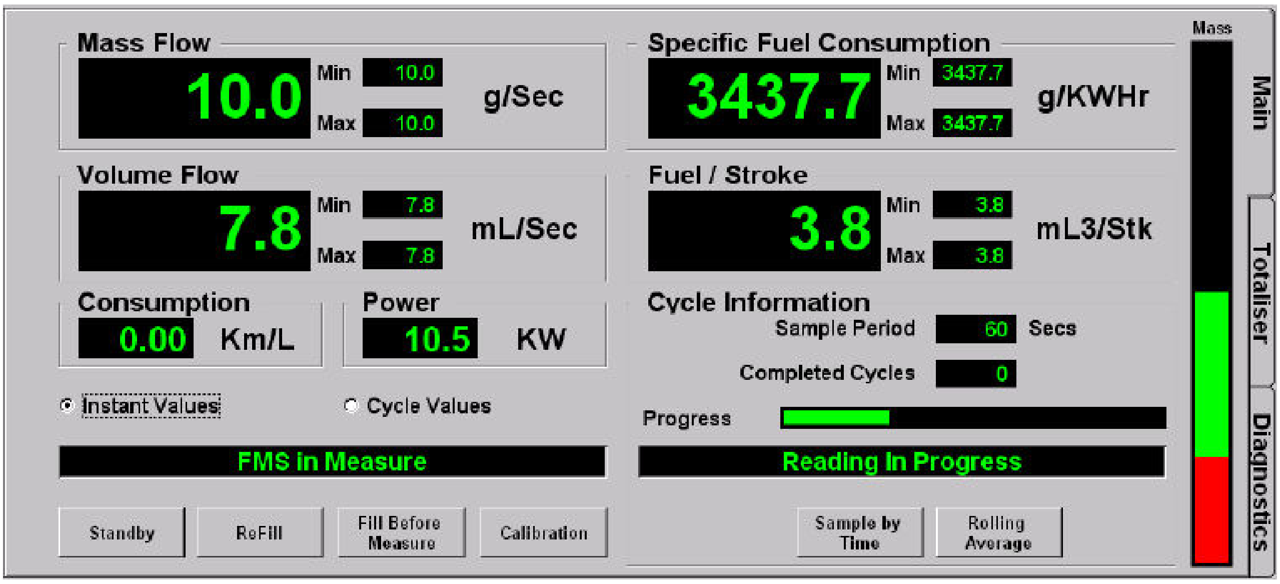


Figure 4: Fuel measurement system main display panel

Selecting the Calibration button within the main display panel of the FMS1000 initiates an automatic calibration sequence. Firstly the FMS checks that the engine is at zero speed and that the fuel level is between the operating masses with no fuel flowing. Calibration is achieved by automatic application of a 100g calibration weight on to the fuel vessel. The resulting increase in the analogue output signal is used to calibrate the system at the prevailing fuel level. Pressing the Save Calibration button stores the calibration results for all future test runs.

The flow range of the FMS100 fuel weigher is 0 to 300 kg/hr and it can operate over a temperature range of 0 to 65ºC. After calibration, according to manufacturers specifications, the accuracy of the physical FMS1000 apparatus and channel is quoted at ±0.05% of reading, ±0.03 g.

Phase III Test Procedure

The SCADA system was first used to develop a program that would demonstrate the flow rates and engine loads experienced during a trawling excursion. These test run engine set points when reduced down to prevent repetition, numbered six separate test points, outlined in Table 1.

Table 1: Engine set points for flow meter test runs

Set point Description	Engine Speed (rpm)	Dynamometer Load (Nm)	Nominal Fuel Consumption (litre/hour)
Idle	1100	0	2.00
Gentle Cruise	1300	36.7	2.50
Steam	2000	47.0	5.85
Cruise & Shoot	1500	38.2	3.75
Trawl	1750	278.1	13.90
Haul	1400	82.5	4.60

This formed the basis of the test cycle. The idle test point was repeated at the end, to ensure that nothing within the system had changed over the course of the test.

The engine test cell SCADA system works by setting the current in the dynamometer coils to provide a torsional load, measuring the load via a load cell, and adjusting the engine rack position until the correct engine speed and dynamometer load are achieved. Between each test run set point ten seconds are given to allow the system to "ramp" to the new values. Then a further 50 seconds settling time are given before logging starts. Average values for the 5 second period from the FMS 1000 and the fuel meter under test are then logged every five seconds for four minutes.

The test procedure involves the simultaneous acquisition of:

- the timestamp from the SCADA system
- the output signal of the flow meter under test, mapped to the range 0-10V by the RTU
- the fuel consumption recorded by the FMS1000, and;
- ambient temperature, (to permit a fuel density correction to be applied)

at 5-second intervals throughout each each test run.

Since a thermometer was not installed in the fuel line, the fuel is taken to be at ambient temperature of the test chamber as it passes through the meter.

Each sequence of test run set points was repeated in full three times for each fuel meter tested.

Data Analysis

In operation, after a short settling time, the net mass of fuel in the vessel is measured. The CP128 card samples data from the physical apparatus at 10 kHz and returns average values back to the SCADA system at 10 Hz. Thus one of these average values is itself an average of 1000 observations, each such observation being subject to the sensor accuracy specifications.

Through Monte Carlo simulation, the standard deviation associated with these averages was found to be 0.0008% of the observation, equivalent to 0.0078g when the vessel is full (~1000g). The SCADA software uses these 0.1 second averages to determine so-called '*instantaneous mass flow rates'* by taking differences of masses over 0.1 second intervals. So called *'cycle mass flow rates'* are determined by differencing masses across a defined cycle period. As the SCADA system clock (equivalently a pulse counter) operates in the MHz range, the uncertainty associated with timings across the cycle period is effectively nil and the cycle mass flow rate is arithmetically equivalent to the average of the instantaneous mass flow rates–**providing the physical flow rate remains constant**.

For Phase III of this work, cycle durations of 5 seconds, 20 seconds and 240 seconds were considered. By means of Monte Carlo analysis, the standard deviations of cycle mass flow rates were established for an initial mass in the fuel weigher of 1000g, and varying mass flow rates. These are reported in Figure 5 below.

An example interpretation, by way of illustration, is as follows. The graph indicates that at a mass flow rate of 10 l/h (2.417 g/s), the standard deviation of observations from the FMS1000 (in the absence of other effects such as fuel pulsation) will be:

- 0.1 l/h (0.024 g/s), if the cycle period is 5 seconds,
- 0.023 l/h (0.0056 g/s), if the cycle period is 20 seconds (equivalent to the standard deviation of averages of sets of 4 contiguous 5 second cycle mass flow rates),
- 0.002 l/h (0.00048 g/s), if the cycle period is 240 seconds (equivalent to the standard deviation of averages of sets of 48 contiguous 5 second cycle mass flow rates, or the standard deviation of averages of sets of 12 contiguous 20 second cycle mass flow rates).

The reason for the equivalences is due to the fact that cycle mass flow rates determined over any cycle period are all based on the uncertainty associated with the mass values recorded at 10 Hz.

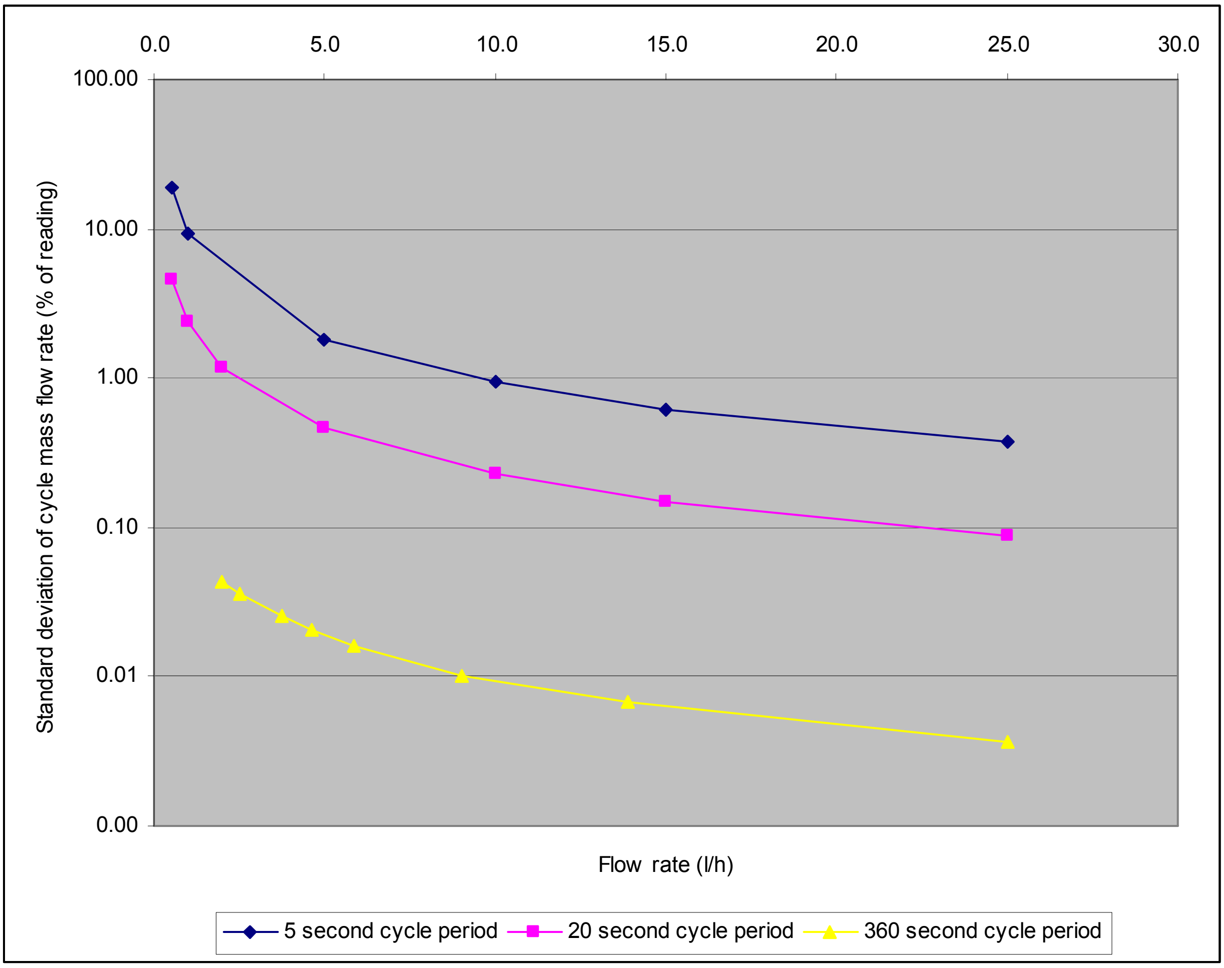


Figure 5: Standard deviation of cycle mass flow rates versus flow rate, for an initial fuel weigher mass of 1000g.

The result of the analysis of uncertainty associated with observations made using the FMS1000 fuel weigher is that mass flow rate observations of very high precision can be obtained with 240 second cycle durations, but these must assume that the physical flow rate remains absolutely steady over this 4 minute period. As the cycle duration reduces, so the proportion of variance in observations that must be attributed to the characteristics of the FMS1000 system must increase. An example used to illustrate this idea follows.

Suppose that the nominal fuel consumption rate of the test engine at a given set point is 10 l/h (2.417 g/s). If the cycle duration is 20 seconds then the standard deviation of the cycle mass flow rate would be expected to be 0.023 l/h. If the actual standard deviation of the 20 second cycle FMS1000 mass flow rates is computed to be 0.056 l/h, then half of the variance in the data could be attributed to the FMS1000 sensor and its channel, and the other half of the variance attributed to external factors, such as engine stability. As four minutes was the total duration of logging of any set point in the tests, it is not possible to compute the standard deviation of cycle flow rates from observations using this cycle period (because there is effectively only one observation). If a cycle duration of 5 seconds was used, then the variance associated with the FMS1000 and its channel may swamp additional variance arising from external factors.

For these reasons, a cycle duration of 20 seconds was chosen for each set point of each test with the flow meter. In the test results sheets that follow, the measured flow rate values are averages of 12, 20 second cycle FMS1000 flow rates and hence should be expected to have a standard deviation following the 240 second curve in Figure 5. This means they will be very accurate. The variance of measured flow figures presented, are computed on the same set of 12, 20 second cycle flow rates and hence should be compared with the 20 second curve in Figure 5.

While this may seem unusual (to quote an average value and a standard deviation on different cycle duration bases) it is consistent with the ultimate objective to compare the relative performance of the various flow meters tested. Data from these sensors and their channels are processed in an identical manner as described for the FMS1000, i.e. 10 Hz averages of analogue signals are themselves averaged over their number in the cycle period. The central difference is that the accuracy and precision of the physical sensor and its channel are assumed unknown, but are to be determined.

For each test and each set point within each test, the FMS1000 and the meter under test face the same variance arising from external factors. As the variance arising from the FMS1000 has been determined for a 20 second cycle period, this can be subtracted from the variance in FMS1000 observations to allow the variance in external factors to be characterised. In turn, the variance in external factors can be subtracted from the variance in the 20 second cycle period indicated flow rate values to isolate their precision.

The 240 second cycle period used for the FMS flow rate values and the indicated flow rate values will allow permit an independent assessment of accuracy of the flow meters under test to be made, for both the ‘out-of-the-box’ situation, and for the ‘after calibration’ situation. In the latter, the calibration parameters determined from the Phase II calibration are used; the flow meter under test does not undergo a second recalibration against the FMS1000 standard.

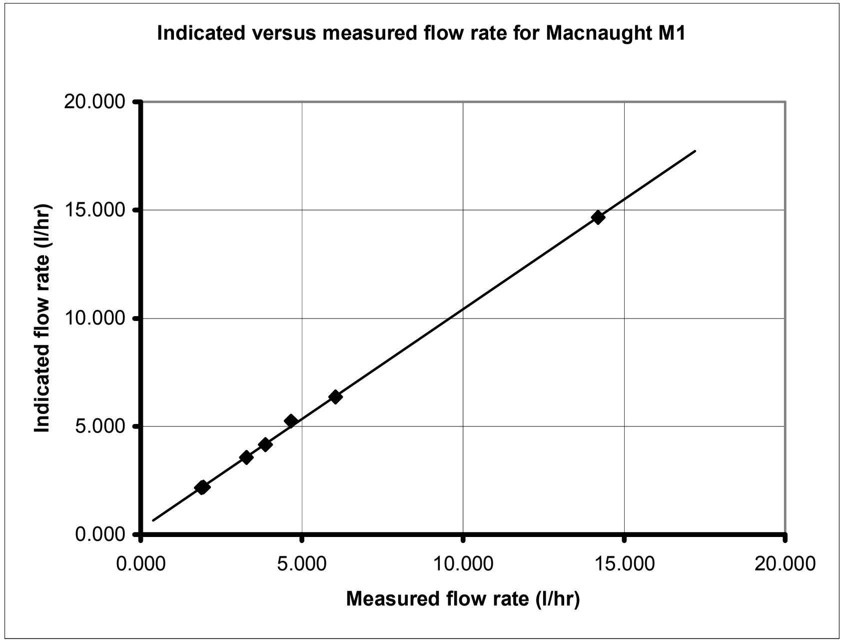
Macnaught M1 Results

Engine Flow Summary 1

Macnaught M1

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l
Idle	2.0	1.881	2.165	0.115	0.132
Idle	2.0	1.952	2.203	0.119	0.135
Gentle Cruise	2.5	3.278	3.564	0.200	0.218
Cruise & Shoot	3.8	3.870	4.157	0.236	0.254
Haul	4.6	4.666	5.254	0.285	0.321
Steam	5.9	6.051	6.367	0.370	0.389
Trawl	13.9	14.196	14.664	0.868	0.896

Inaccuracy in Indicated Flow Rate		Inaccuracy in Indicated Cumulative Volume		Variance of Indicated Flow $(l/hr)^2$	Variance of Measured Flow $(l/hr)^2$
% measured	% full scale	% measured	% full scale		
15.08	0.28	14.83	0.28	0.00017	0.00013
12.86	0.25	12.86	0.25	0.00044	0.00025
8.70	0.29	8.70	0.29	0.00044	0.00016
7.44	0.29	7.44	0.29	0.00084	0.00031
12.62	0.59	12.61	0.59	0.08982	0.00119
5.23	0.32	5.23	0.32	0.00132	0.00159
3.30	0.47	3.30	0.47	0.01292	0.00213



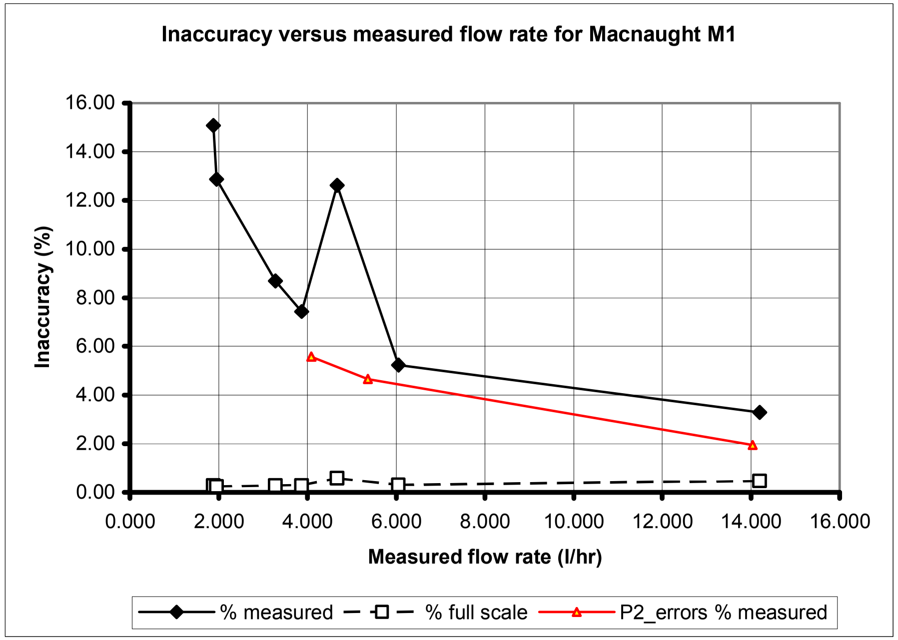


Table 2: "Out-of-the-box" performance of the Macnaught M1 fuel flow meter, repetition 1

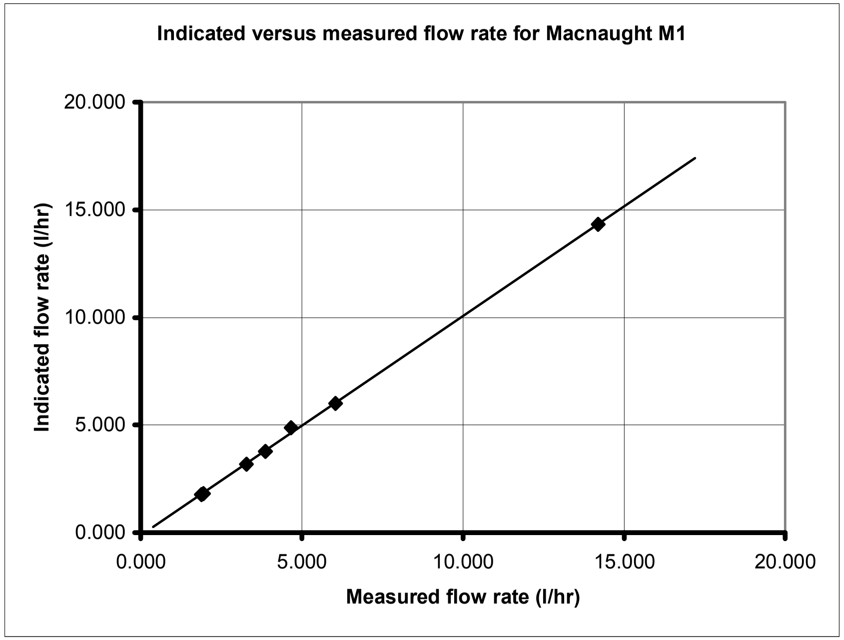
Recalibrated

Engine Flow Summary 1

Macnaught M1

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l
Idle	2.0	1.881	1.776	0.115	0.108
Idle	2.0	1.952	1.815	0.119	0.111
Gentle Cruise	2.5	3.278	3.180	0.200	0.194
Cruise & Shoot	3.8	3.870	3.777	0.236	0.231
Haul	4.6	4.666	4.878	0.285	0.298
Steam	5.9	6.051	5.995	0.370	0.366
Trawl	13.9	14.196	14.324	0.868	0.875

Inaccuracy in Indicated Flow Rate		Inaccuracy in Indicated Cumulative Volume		Variance of Indicated Flow $(l/hr)^2$	Variance of Measured Flow $(l/hr)^2$
% measured	% full scale	% measured	% full scale		
-5.58	-0.10	-5.78	-0.11	0.00018	0.00013
-7.03	-0.14	-7.03	-0.14	0.00044	0.00025
-2.99	-0.10	-2.99	-0.10	0.00044	0.00016
-2.40	-0.09	-2.40	0.21	0.00085	0.00031
4.55	0.21	4.54	0.21	0.09052	0.00119
-0.92	-0.06	-0.92	-0.06	0.00133	0.00159
0.90	0.13	0.90	0.13	0.01302	0.00213



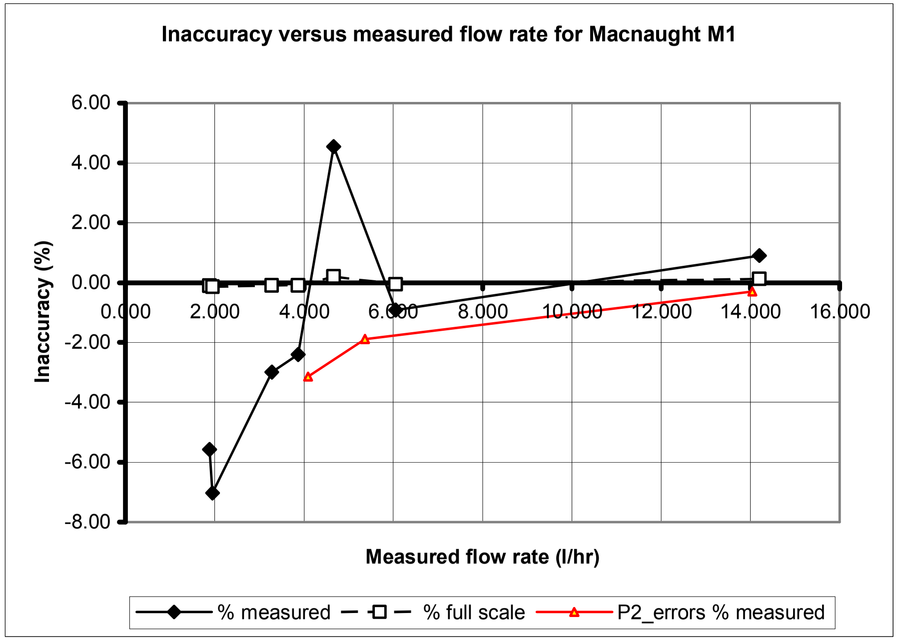


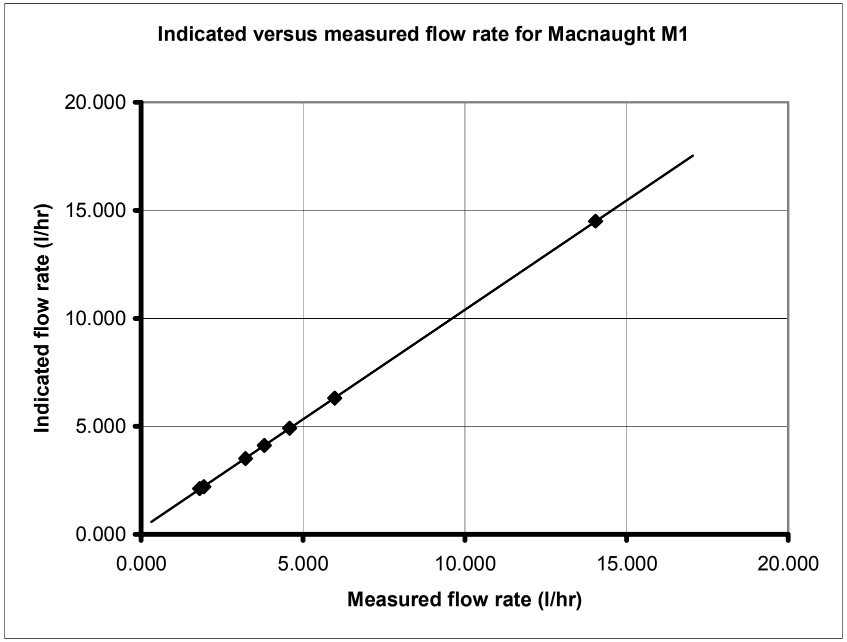
Table 3: "Recalibrated" performance of the Macnaught M1 fuel flow meter, repetition 1

Engine Flow Summary 2

Macnaught M1

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l
Idle	2.0	1.810	2.117	0.111	0.129
Idle	2.0	1.932	2.205	0.118	0.135
Gentle Cruise	2.5	3.225	3.515	0.197	0.215
Cruise & Shoot	3.8	3.807	4.114	0.233	0.251
Haul	4.6	4.581	4.914	0.280	0.300
Steam	5.9	5.982	6.316	0.366	0.386
Trawl	13.9	14.043	14.500	0.858	0.886

Inaccuracy in Indicated Flow Rate		Inaccuracy in Indicated Cumulative Volume		Variance of Indicated Flow $(l/hr)^2$	Variance of Measured Flow $(l/hr)^2$
% measured	% full scale	% measured	% full scale		
16.95	0.31	16.96	0.31	0.00189	0.00071
14.15	0.27	14.15	0.27	0.00040	0.00041
8.97	0.29	8.98	0.29	0.00040	0.00067
8.08	0.31	8.09	0.31	0.00154	0.00139
7.27	0.33	7.28	0.33	0.00104	0.00247
5.58	0.33	5.59	0.33	0.00169	0.00480
3.26	0.46	3.27	0.46	0.01208	0.02219



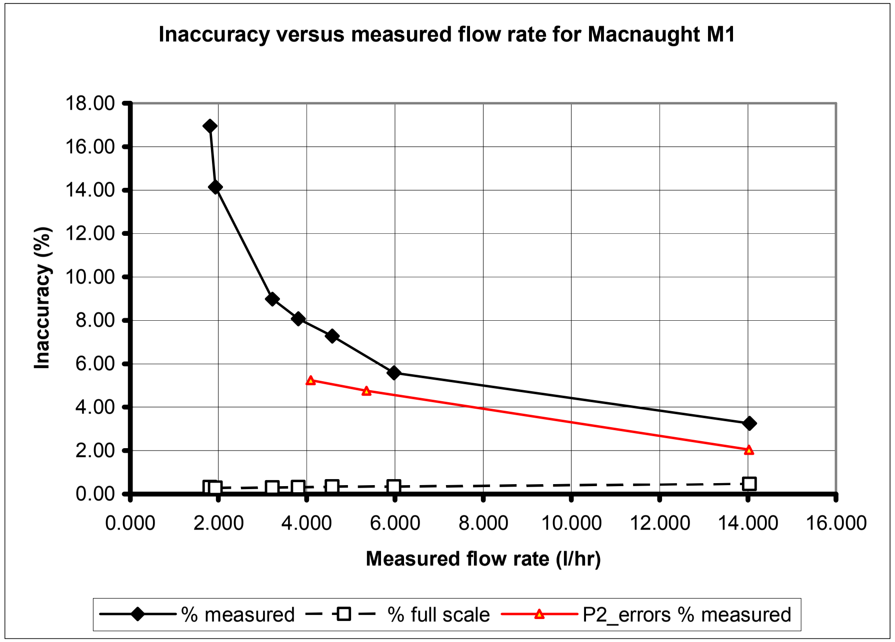


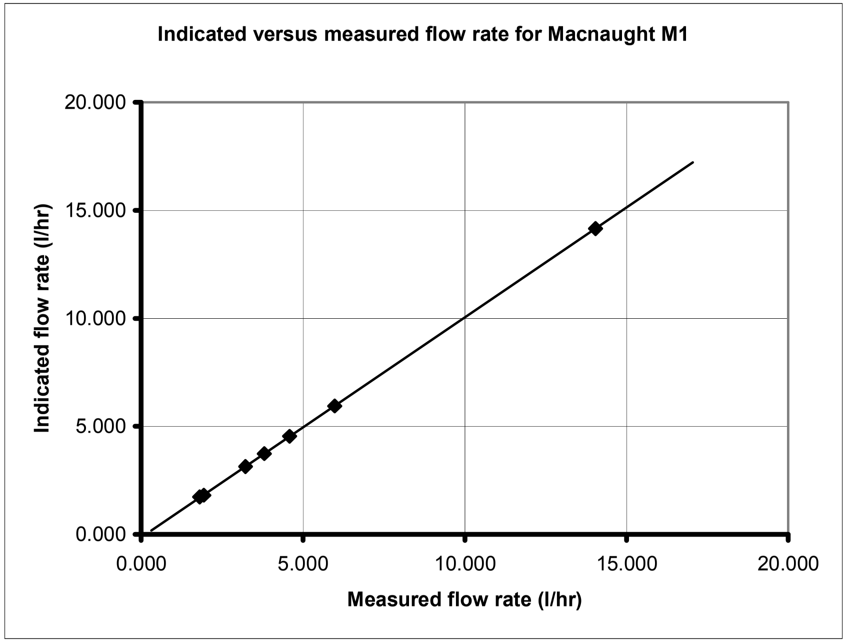
Table 4: "Out-of-the-box" performance of the Macnaught M1 fuel flow meter, repetition 2

Recalibrated

Engine Flow Summary 2

Macnaught M1

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l	Inaccuracy in Indicated Flow Rate % measured	Inaccuracy in Indicated Flow Rate % full scale	Inaccuracy in Indicated Cumulative Volume % measured	Inaccuracy in Indicated Cumulative Volume % full scale	Variance of Indicated Flow $(l/hr)^2$	Variance of Measured Flow $(l/hr)^2$
Idle	2.0	1.810	1.728	0.111	0.106	-4.53	-0.08	-4.52	-0.08	0.00190	0.00071
Idle	2.0	1.932	1.817	0.118	0.111	-5.96	-0.12	-5.95	-0.11	0.00040	0.00041
Gentle Cruise	2.5	3.225	3.132	0.197	0.191	-2.91	-0.09	-2.90	-0.09	0.00040	0.00067
Cruise & Shoot	3.8	3.807	3.733	0.233	0.228	-1.93	-0.07	-1.92	-0.07	0.00155	0.00139
Haul	4.6	4.581	4.536	0.280	0.277	-0.98	-0.04	-0.97	-0.04	0.00105	0.00247
Steam	5.9	5.982	5.944	0.366	0.363	-0.64	-0.04	-0.63	-0.04	0.00171	0.00480
Trawl	13.9	14.043	14.160	0.858	0.865	0.83	0.12	0.84	0.12	0.01217	0.02219



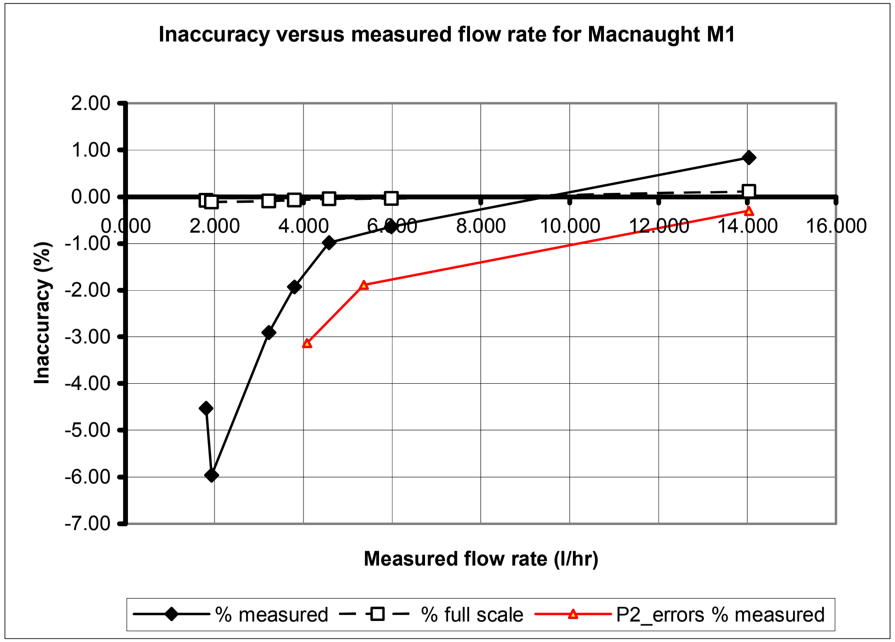


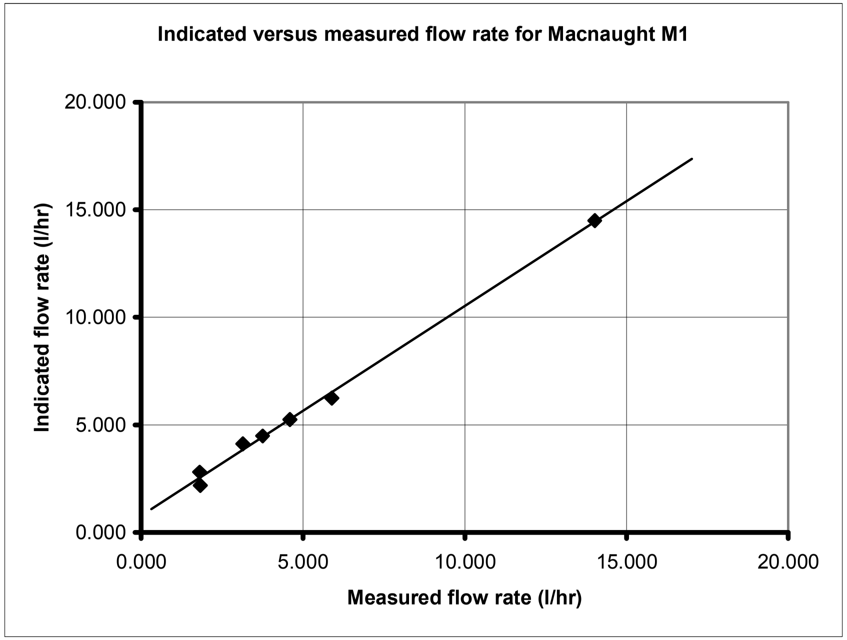
Table 5: "Recalibrated" performance of the Macnaught M1 fuel flow meter, repetition 1

Engine Flow Summary 3

Macnaught M1

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l
Idle	2.0	1.813	2.812	0.111	0.172
Idle	2.0	1.826	2.181	0.112	0.133
Gentle Cruise	2.5	3.137	4.114	0.192	0.251
Cruise & Shoot	3.8	3.746	4.479	0.229	0.274
Haul	4.6	4.595	5.247	0.281	0.321
Steam	5.9	5.889	6.251	0.360	0.382
Trawl	13.9	14.017	14.494	0.857	0.886

Inaccuracy in Indicated Flow Rate		Inaccuracy in Indicated Cumulative Volume		Variance of Indicated Flow $(l/hr)^2$	Variance of Measured Flow $(l/hr)^2$
% measured	% full scale	% measured	% full scale		
55.12	1.00	55.19	1.00	0.14768	0.00062
19.44	0.35	19.44	0.35	0.24095	0.00070
31.12	0.98	31.16	0.98	0.24095	0.00077
19.57	0.73	19.56	0.73	0.16105	0.00122
14.18	0.65	14.19	0.65	0.03979	0.00254
6.14	0.36	6.14	0.36	0.00120	0.00362
3.41	0.48	3.42	0.48	0.00341	0.01967



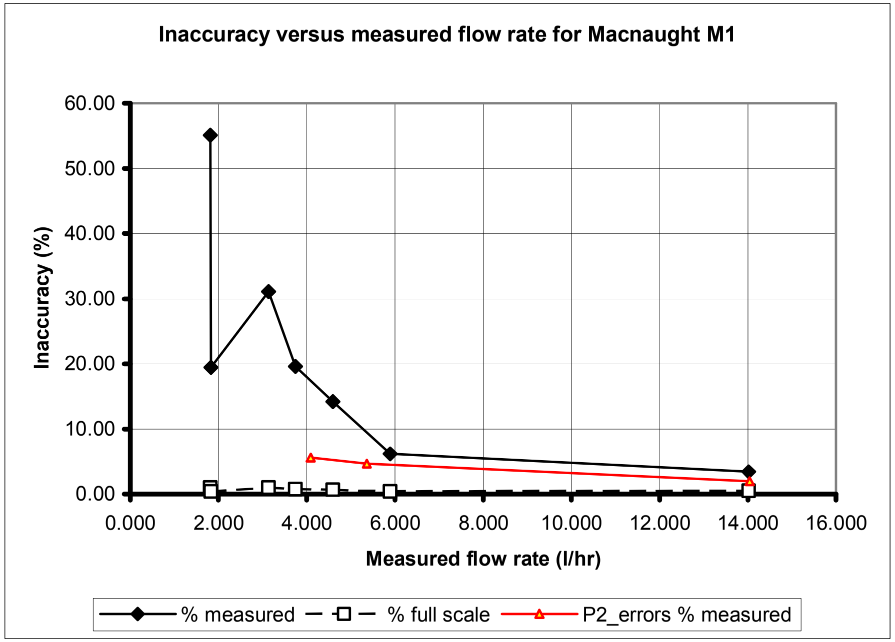


Table 6: "Out-of-the-box" performance of the Macnaught M1 fuel flow meter, repetition 3

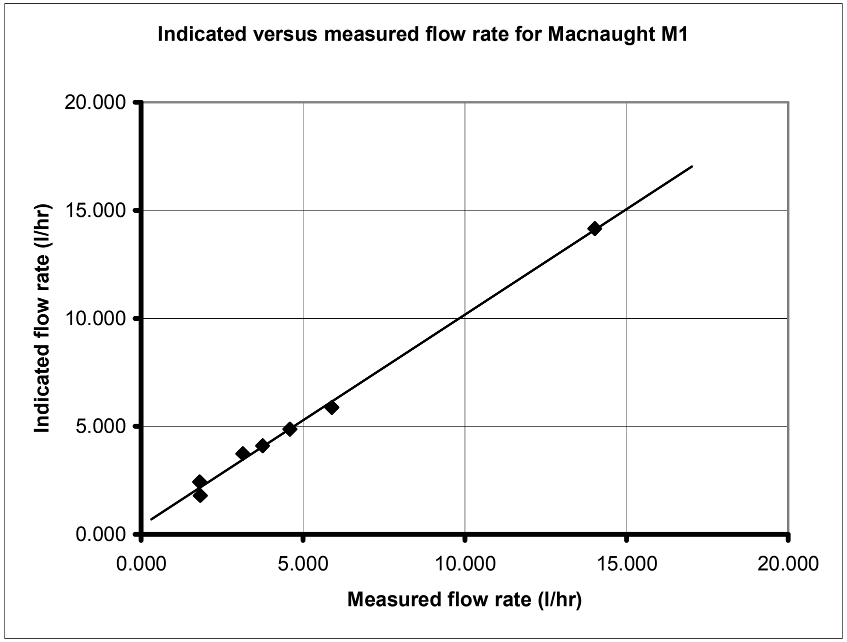
Recalibrated

Engine Flow Summary 3

Macnaught M1

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l
Idle	2.0	1.813	2.426	0.111	0.148
Idle	2.0	1.826	1.792	0.112	0.110
Gentle Cruise	2.5	3.137	3.733	0.192	0.228
Cruise & Shoot	3.8	3.746	4.100	0.229	0.250
Haul	4.6	4.595	4.870	0.281	0.298
Steam	5.9	5.889	5.878	0.360	0.359
Trawl	13.9	14.017	14.154	0.857	0.865

Inaccuracy in Indicated Flow Rate		Inaccuracy in Indicated Cumulative Volume		Variance of Indicated Flow	Variance of Measured Flow
% measured	% full scale	% measured	% full scale	$(l/hr)^2$	$(l/hr)^2$
33.82	0.61	33.90	0.61	0.14883	0.00062
-1.83	-0.03	-1.83	-0.03	0.24283	0.00070
18.98	0.60	19.01	0.60	0.24283	0.00077
9.44	0.35	9.43	0.35	0.16231	0.00122
5.99	0.28	5.99	0.28	0.04010	0.00254
-0.19	-0.01	-0.18	-0.01	0.00121	0.00362
0.98	0.14	0.99	0.14	0.00344	0.01967



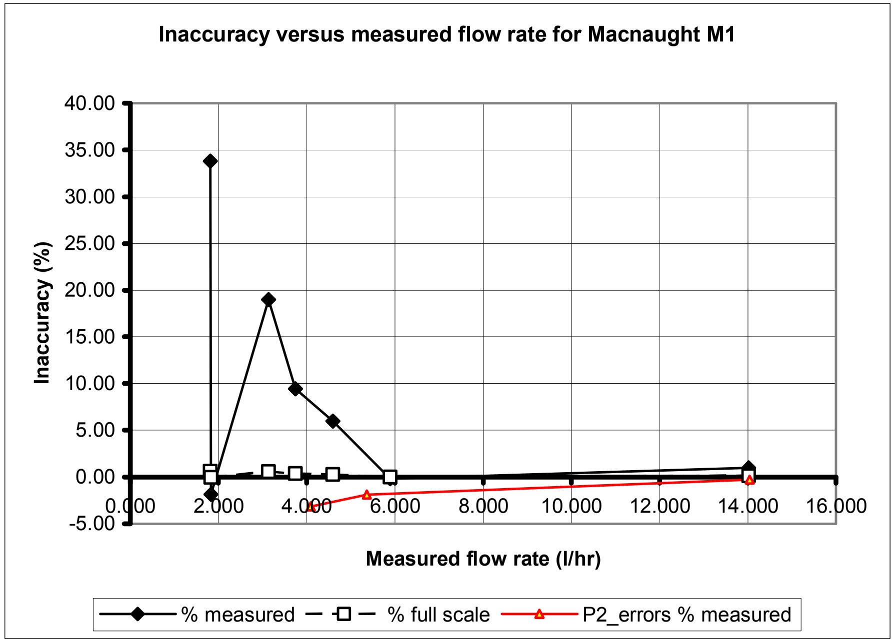


Table 7: "Recalibrated" performance of the Macnaught M1 fuel flow meter, repetition 3

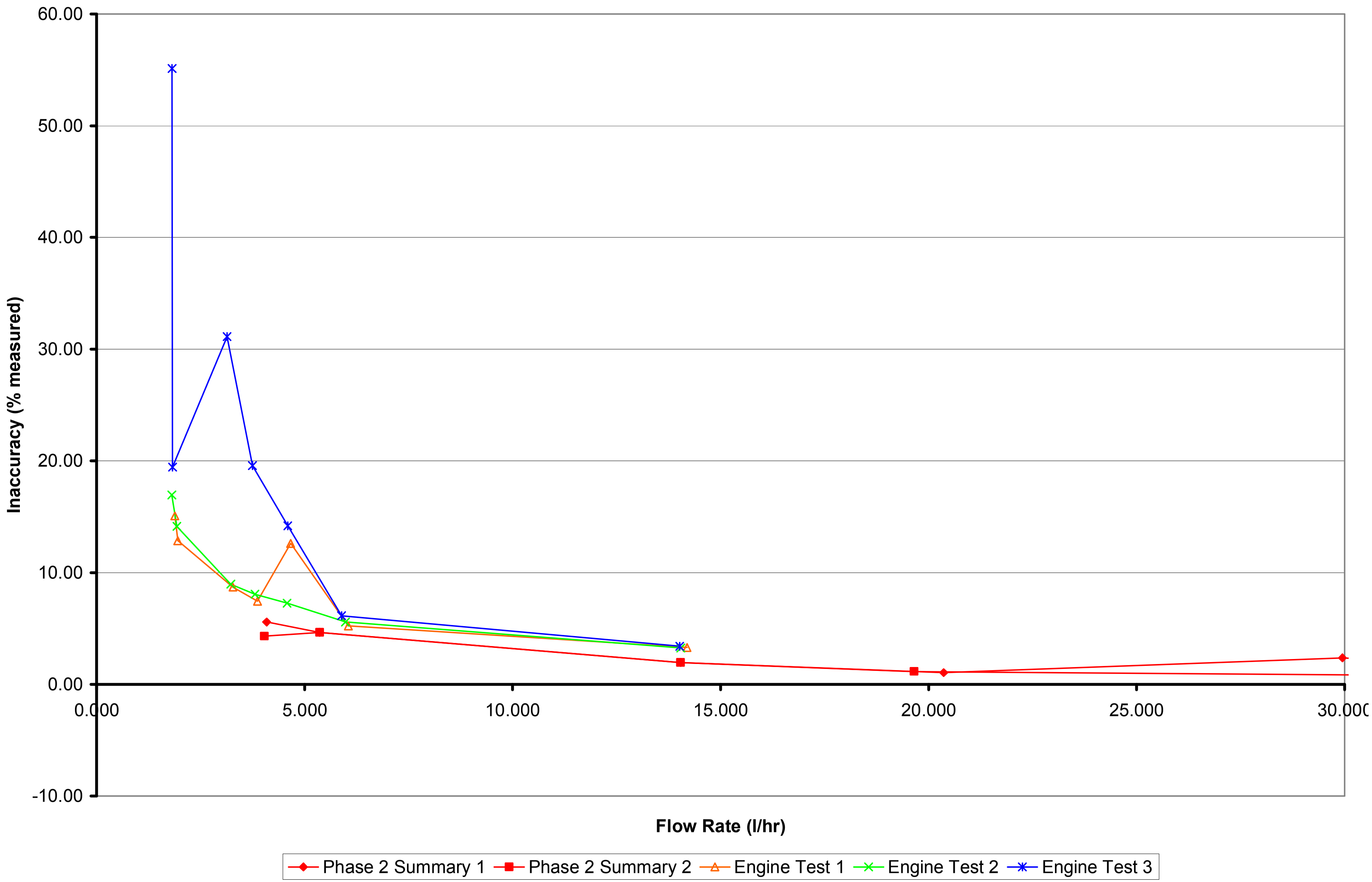


Figure 6: Accuracy versus flowrate for Macnaught M1 fuel flow meter – "out-of-the-box"

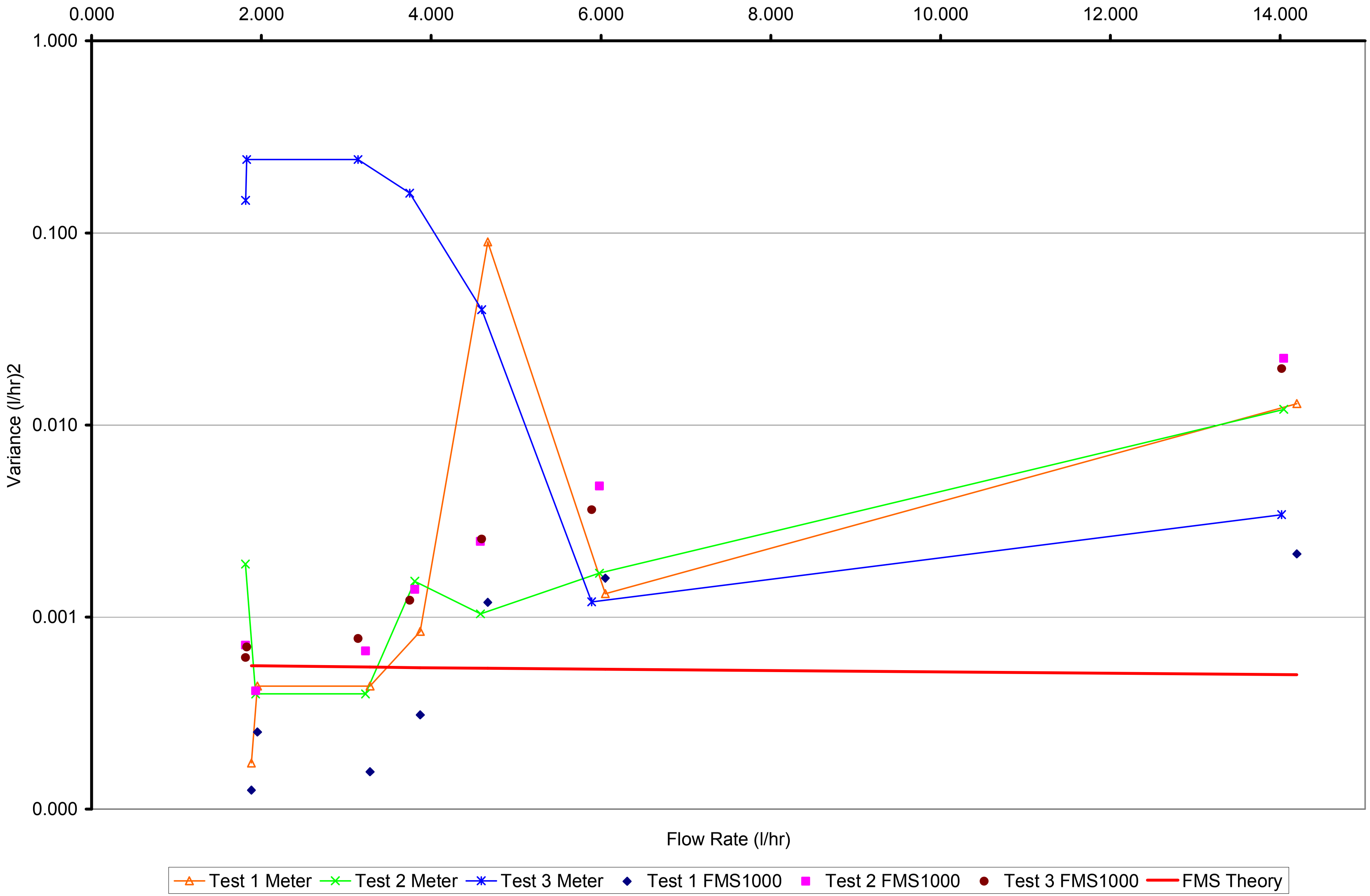


Figure 7: Variance versus flowrate for Macnaught M1 fuel flow meter – “out-of-the-box”

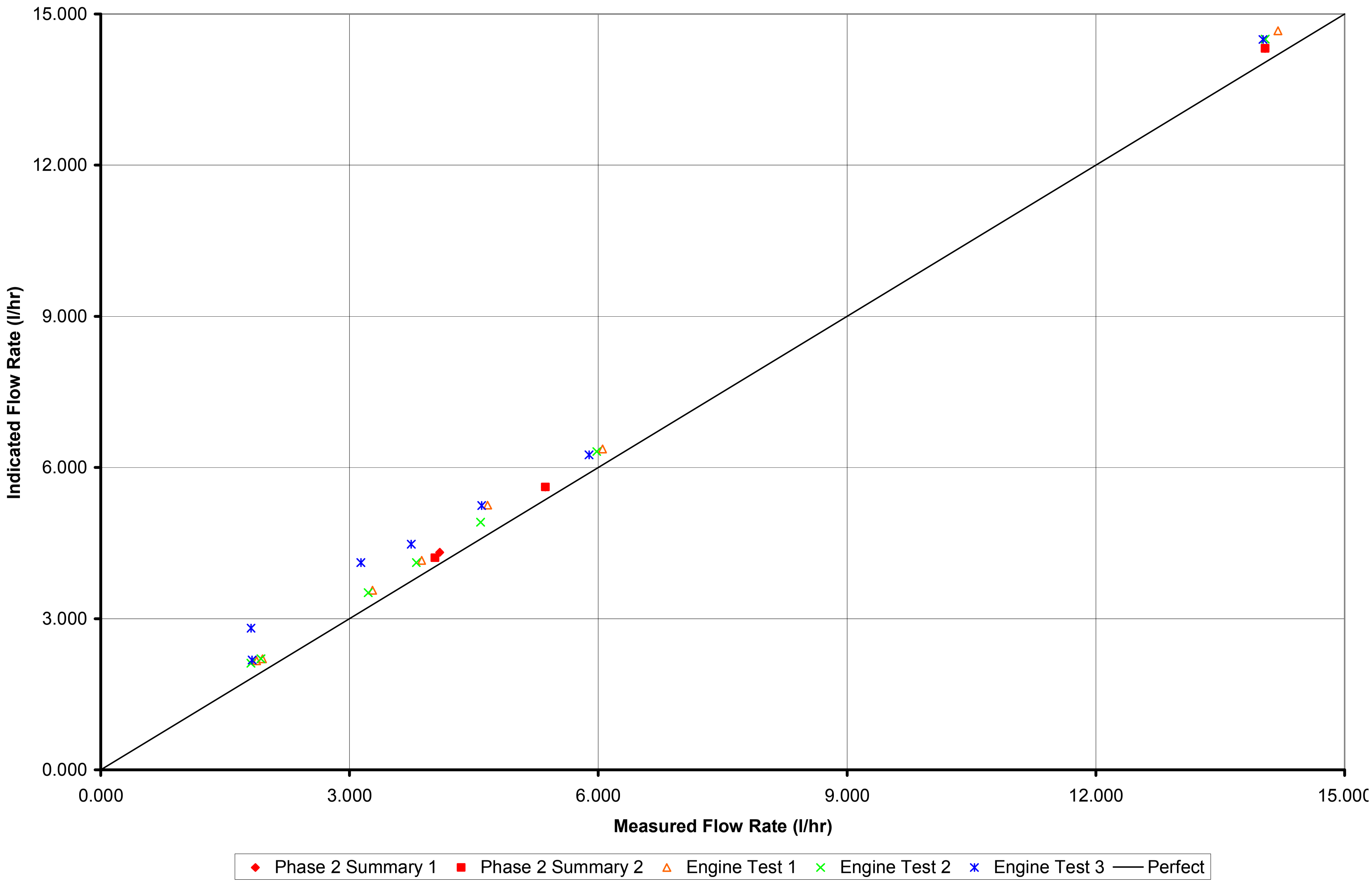


Figure 8: Indicated versus measured flowrate for Macnaught M1 fuel flow meter – "out-of-the-box"

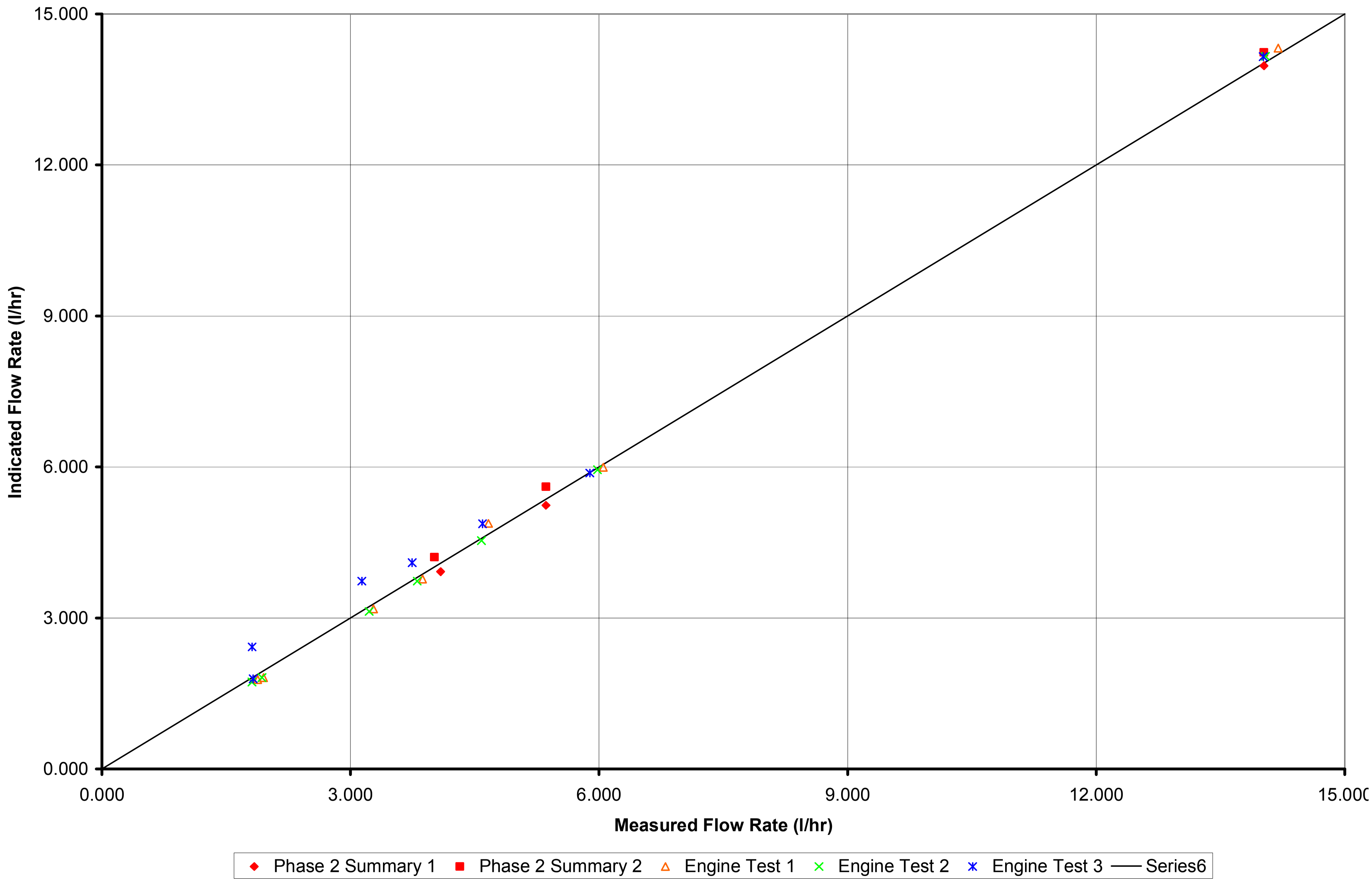
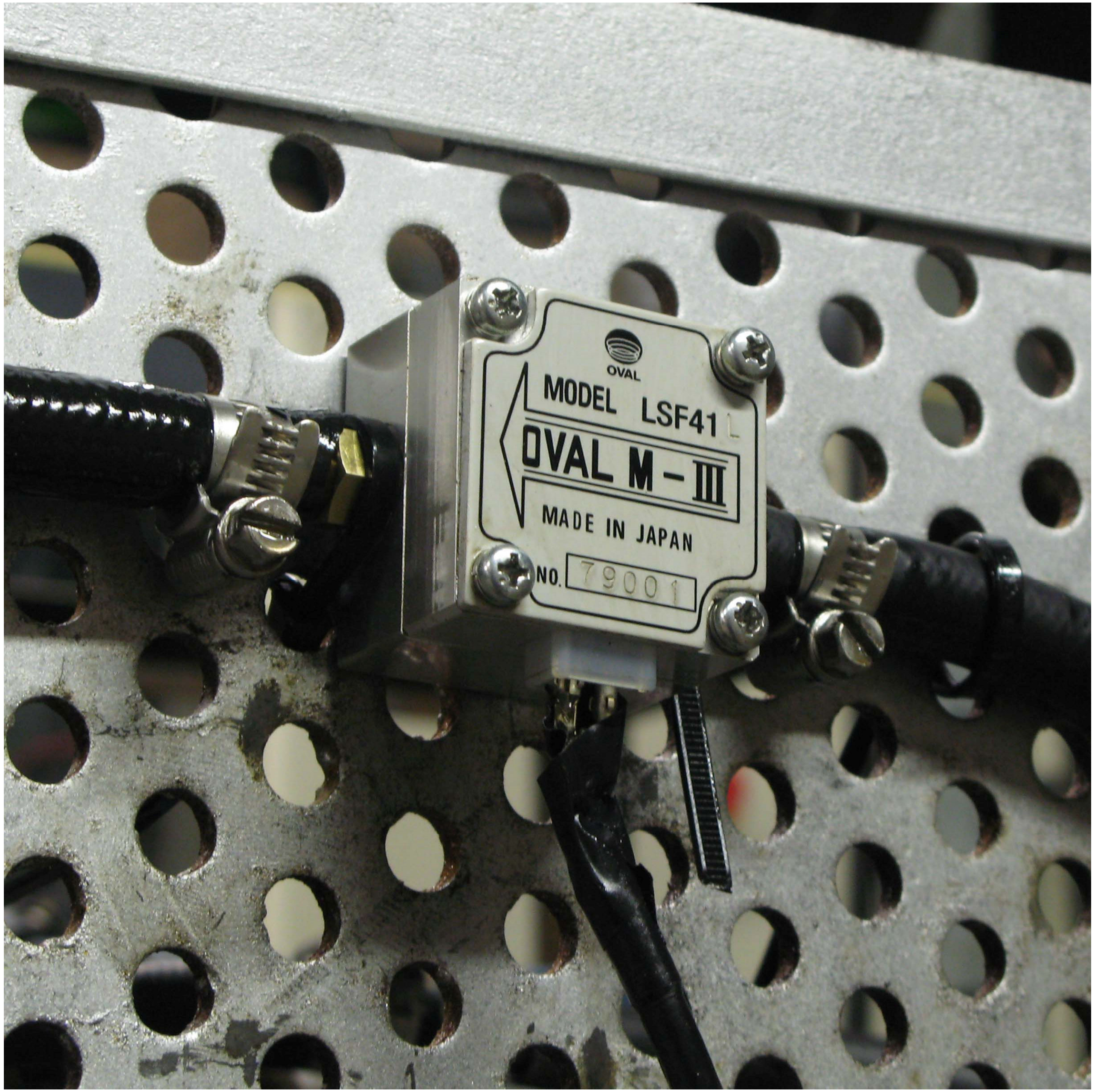


Figure 9: Indicated versus measured flowrate for Macnaught M1 fuel flow meter – after Phase II calibration

Discussion

Over this range, it is easier to see the flaws in the linearity of this device, but, on the whole, it has performed well, generally performing to specification (inaccuracy $< 0.5\%$ of full scale). The third test run on the whole shows some very unexpected outlying values. The inaccuracy is small enough throughout such that it cannot be conclusively stated that being on an engine affected the reading of this device at all, this being within the uncertainty of our logging system.

OVAL MIII Flowmate Results

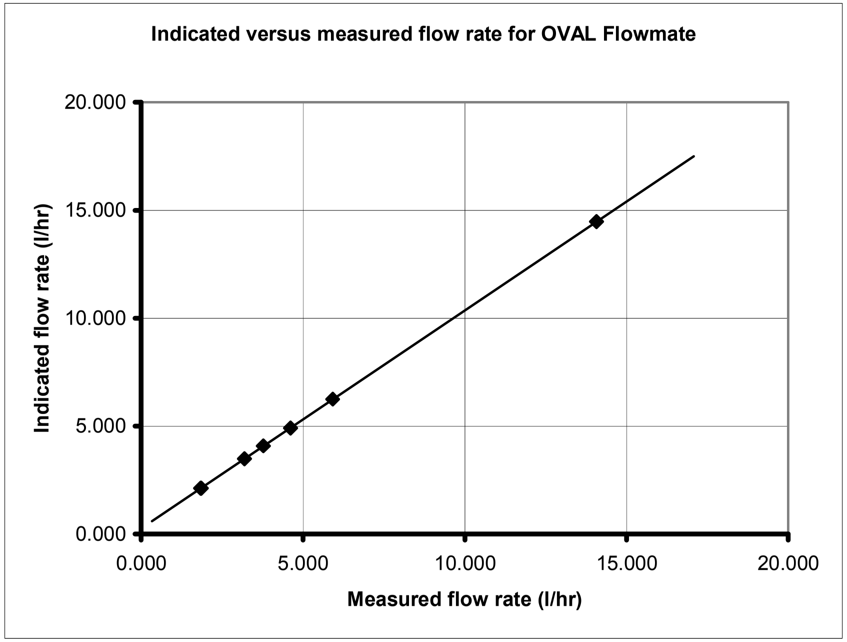


Engine Flow Summary 1

OVAL Flowmate

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l
Idle	2.0	1.837	2.127	0.112	0.130
Idle	2.0	1.856	2.125	0.113	0.130
Gentle Cruise	2.5	3.192	3.490	0.195	0.213
Cruise & Shoot	3.8	3.777	4.086	0.231	0.250
Haul	4.6	4.610	4.912	0.282	0.300
Steam	5.9	5.919	6.256	0.362	0.382
Trawl	13.9	14.076	14.469	0.860	0.884

Inaccuracy in Indicated Flow Rate		Inaccuracy in Indicated Cumulative Volume		Variance of Indicated Flow	Variance of Measured Flow
% measured	% full scale	% measured	% full scale	$(l/hr)^2$	$(l/hr)^2$
15.76	0.29	15.50	0.29	0.00015	0.00013
14.54	0.27	14.54	0.27	0.00016	0.00042
9.34	0.30	9.34	0.30	0.00016	0.00018
8.17	0.31	8.17	0.31	0.00043	0.00028
6.56	0.30	6.56	0.30	0.00097	0.00150
5.68	0.34	5.68	0.34	0.00080	0.00108
2.79	0.39	2.79	0.39	0.00302	0.00233



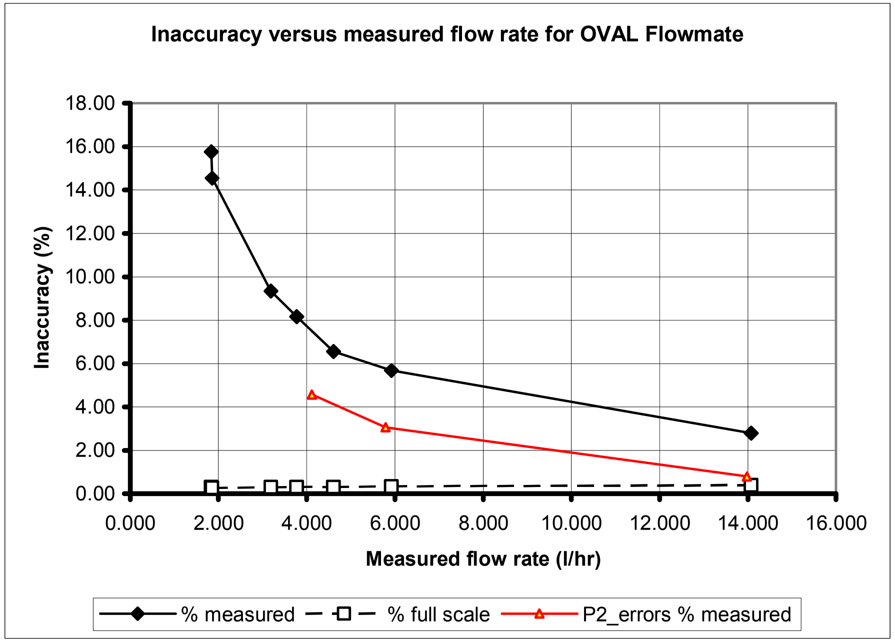


Table 8: "Out-of-the-box" performance of the Oval Flowmate MIII fuel flow meter, repetition 1

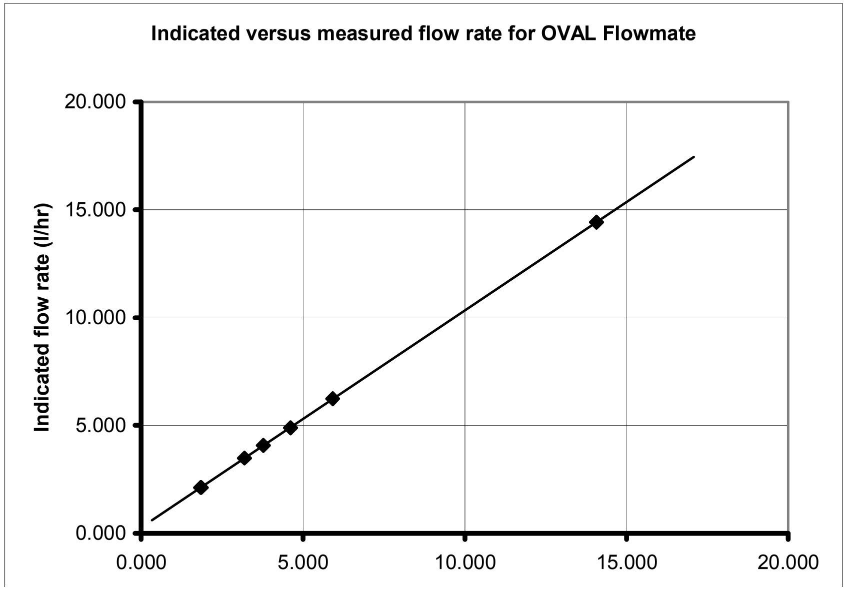
Recalibrated

Engine Flow Summary 1

OVAL Flowmate

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l
Idle	2.0	1.837	2.120	0.112	0.129
Idle	2.0	1.856	2.118	0.113	0.129
Gentle Cruise	2.5	3.192	3.479	0.195	0.213
Cruise & Shoot	3.8	3.777	4.072	0.231	0.249
Haul	4.6	4.610	4.896	0.282	0.299
Steam	5.9	5.919	6.235	0.362	0.381
Trawl	13.9	14.076	14.422	0.860	0.881

Inaccuracy in Indicated Flow Rate		Inaccuracy in Indicated Cumulative Volume		Variance of Indicated Flow $(l/hr)^2$	Variance of Measured Flow $(l/hr)^2$
% measured	% full scale	% measured	% full scale		
15.38	0.28	15.12	0.28	0.00015	0.00013
14.17	0.26	14.17	0.26	0.00016	0.00042
8.98	0.29	8.98	0.29	0.00016	0.00018
7.81	0.30	7.81	0.29	0.00043	0.00028
6.20	0.29	6.21	0.29	0.00096	0.00150
5.33	0.32	5.33	0.32	0.00079	0.00108
2.45	0.35	2.45	0.35	0.00300	0.00233



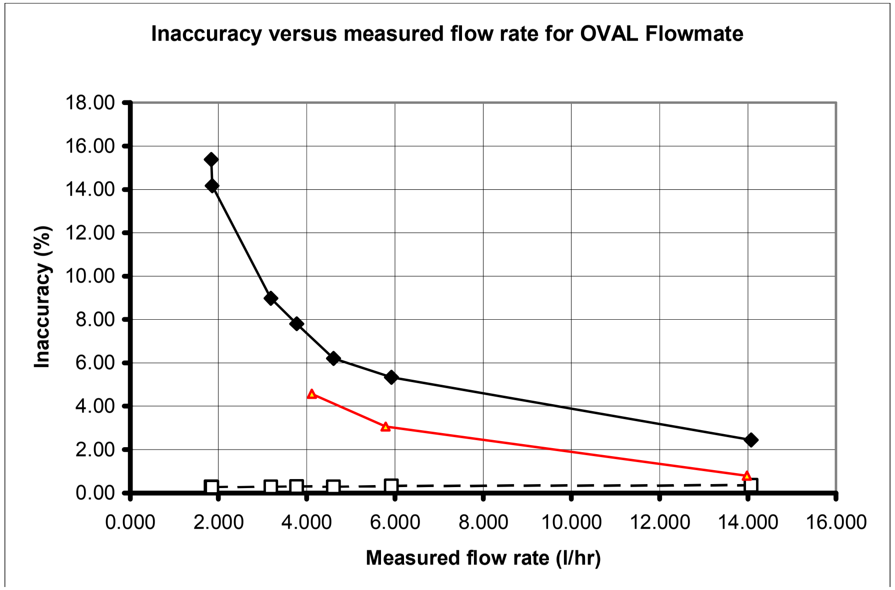


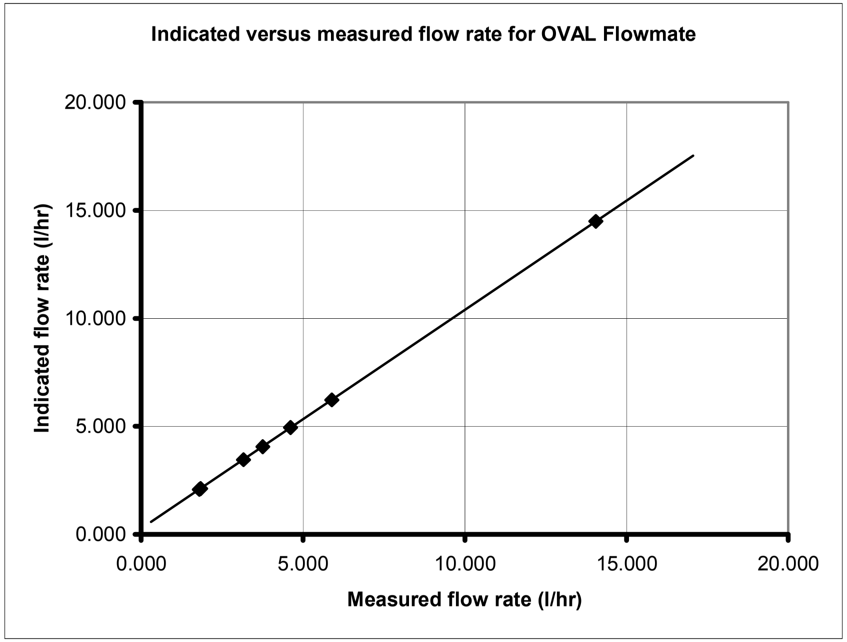
Table 9: "Recalibrated" performance of the Oval Flowmate MIII fuel flow meter, repetition 1

Engine Flow Summary 2

OVAL Flowmate

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l
Idle	2.0	1.834	2.120	0.112	0.130
Idle	2.0	1.803	2.085	0.110	0.127
Gentle Cruise	2.5	3.163	3.457	0.193	0.211
Cruise & Shoot	3.8	3.759	4.067	0.230	0.249
Haul	4.6	4.611	4.941	0.282	0.302
Steam	5.9	5.885	6.222	0.360	0.380
Trawl	13.9	14.057	14.489	0.859	0.885

Inaccuracy in Indicated Flow Rate		Inaccuracy in Indicated Cumulative Volume		Variance of Indicated Flow	Variance of Measured Flow
% measured	% full scale	% measured	% full scale	$(l/hr)^2$	$(l/hr)^2$
15.63	0.29	15.63	0.29	0.00026	0.00028
15.68	0.28	15.68	0.28	0.00024	0.00045
9.30	0.29	9.30	0.29	0.00024	0.00015
8.21	0.31	8.21	0.31	0.00044	0.00020
7.16	0.33	7.16	0.33	0.00115	0.00106
5.73	0.34	5.73	0.34	0.00131	0.00119
3.07	0.43	3.07	0.43	0.00500	0.00166



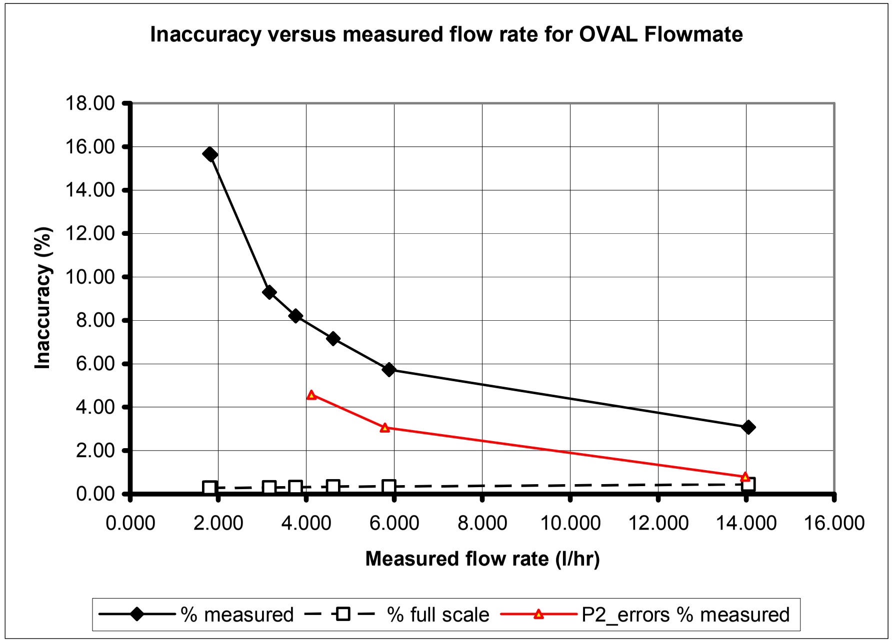


Table 10: "Out-of-the-box" performance of the Oval Flowmate MIII fuel flow meter, repetition 2

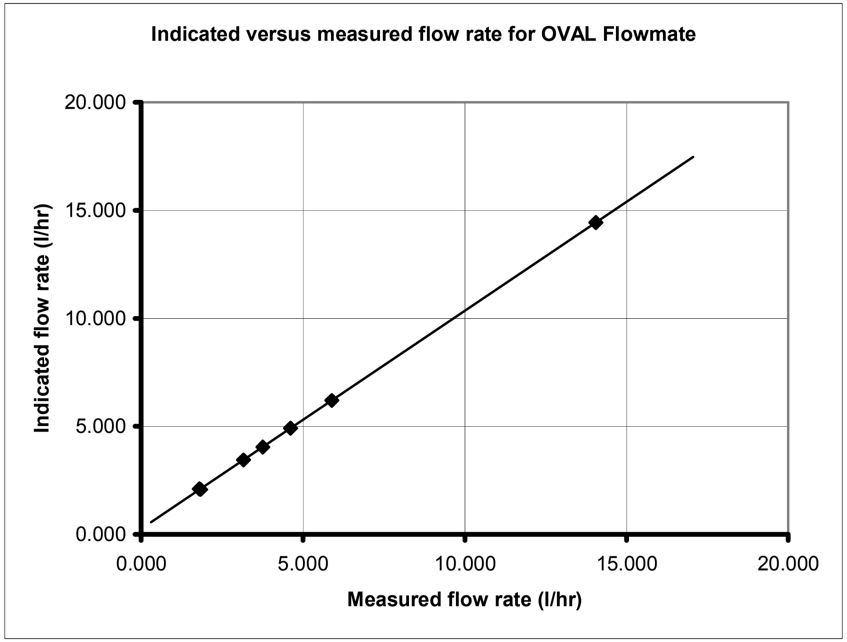
Recalibrated

Engine Flow Summary 2

OVAL Flowmate

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l
Idle	2.0	1.834	2.079	0.110	0.127
Idle	2.0	1.803	2.113	0.112	0.129
Gentle Cruise	2.5	3.163	3.445	0.193	0.211
Cruise & Shoot	3.8	3.759	4.054	0.230	0.248
Haul	4.6	4.611	4.925	0.282	0.301
Steam	5.9	5.885	6.202	0.360	0.379
Trawl	13.9	14.057	14.441	0.859	0.883

Inaccuracy in Indicated Flow Rate		Inaccuracy in Indicated Cumulative Volume		Variance of Indicated Flow $(l/hr)^2$	Variance of Measured Flow $(l/hr)^2$
% measured	% full scale	% measured	% full scale		
13.35	0.24	15.30	0.28	0.00024	0.00028
17.23	0.31	15.25	0.28	0.00026	0.00045
8.94	0.28	8.94	0.28	0.00024	0.00015
6.81	0.31	6.81	0.31	0.00044	0.00020
6.81	0.31	6.81	0.31	0.00114	0.00106
5.38	0.32	5.38	0.32	0.00131	0.00119
2.73	0.38	2.73	0.38	0.00497	0.00166



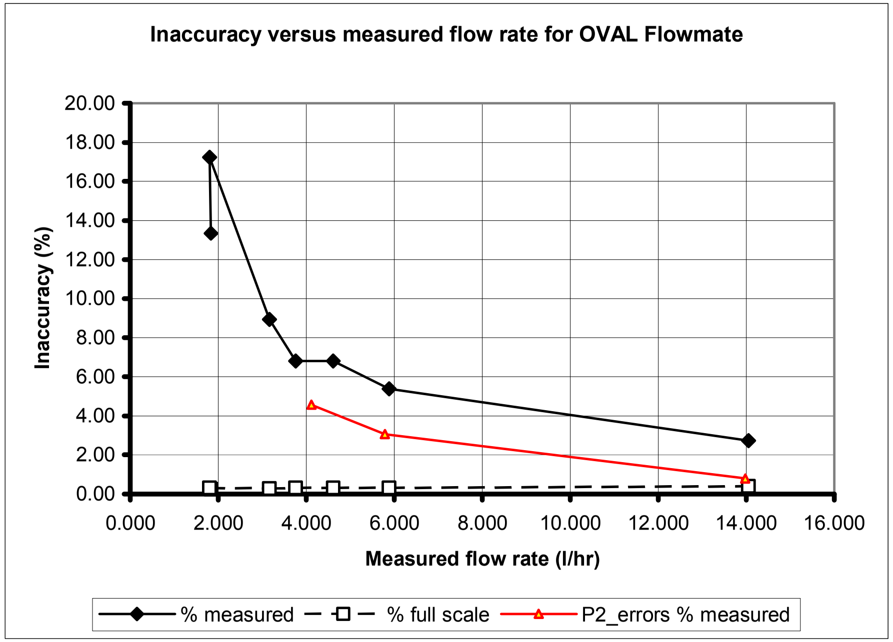


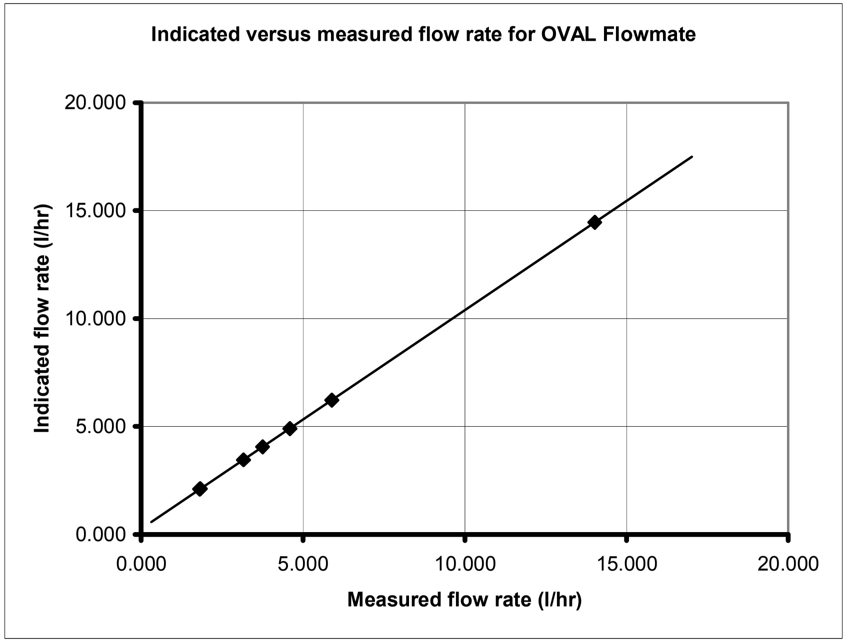
Table 11: "Recalibrated" performance of the Oval Flowmate MIII fuel flow meter, repetition 2

Engine Flow Summary 3

OVAL Flowmate

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Indicated Cumulative Volume l
Idle	2.0	1.825	2.124	0.112	0.130
Idle	2.0	1.809	2.105	0.111	0.129
Gentle Cruise	2.5	3.158	3.462	0.193	0.212
Cruise & Shoot	3.8	3.754	4.062	0.229	0.248
Haul	4.6	4.596	4.905	0.281	0.300
Steam	5.9	5.886	6.232	0.360	0.381
Trawl	13.9	14.021	14.453	0.857	0.883

Inaccuracy in Indicated Flow Rate		Inaccuracy in Indicated Cumulative Volume		Variance of Indicated Flow	Variance of Measured Flow
% measured	% full scale	% measured	% full scale	$(l/hr)^2$	$(l/hr)^2$
16.36	0.30	16.36	0.30	0.00053	0.00064
16.33	0.30	16.34	0.30	0.00032	0.00035
9.63	0.30	9.63	0.30	0.00032	0.00017
8.20	0.31	8.20	0.31	0.00024	0.00036
6.72	0.31	6.72	0.31	0.00139	0.00119
5.88	0.35	5.88	0.35	0.00138	0.00123
3.08	0.43	3.08	0.43	0.00385	0.00188



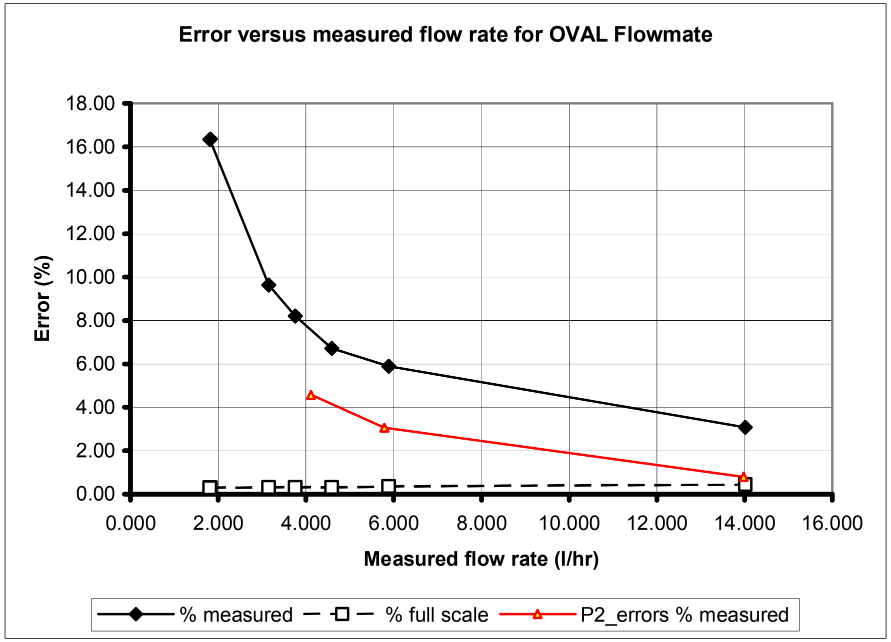


Table 12: "Out-of-the-box" performance of the Oval Flowmate MIII fuel flow meter, repetition 3

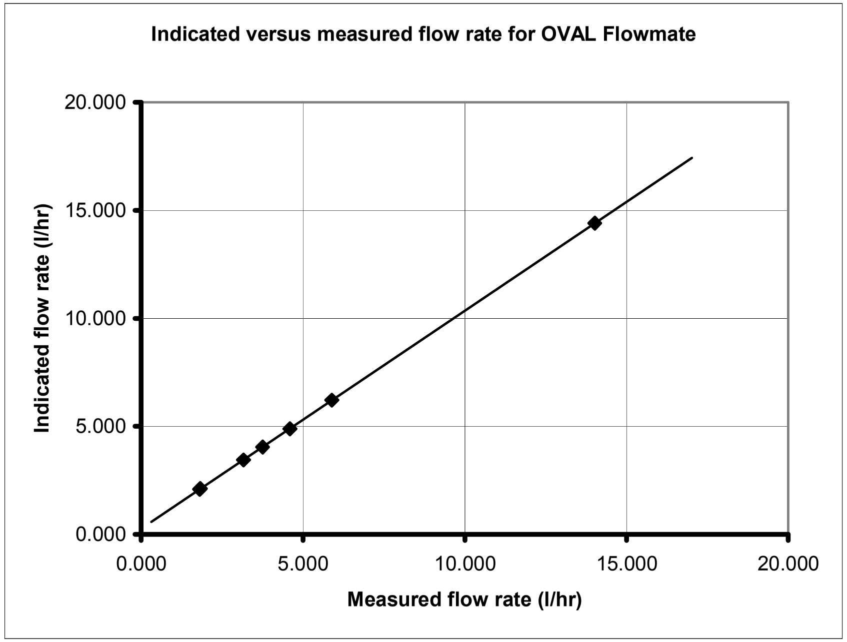
Recalibrated

Engine Flow Summary 3

OVAL Flowmate

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l
Idle	2.0	1.825	2.117	0.112	0.129
Idle	2.0	1.809	2.098	0.111	0.128
Gentle Cruise	2.5	3.158	3.450	0.193	0.211
Cruise & Shoot	3.8	3.754	4.048	0.229	0.247
Haul	4.6	4.596	4.889	0.281	0.299
Steam	5.9	5.886	6.212	0.360	0.380
Trawl	13.9	14.021	14.405	0.857	0.880

Inaccuracy in Indicated Flow Rate		Inaccuracy in Indicated Cumulative Volume		Variance of Indicated Flow	Variance of Measured Flow
% measured	% full scale	% measured	% full scale	$(l/hr)^2$	$(l/hr)^2$
15.97	0.29	15.97	0.29	0.00032	0.00064
15.95	0.29	15.95	0.29	0.00052	0.00035
9.27	0.29	9.27	0.29	0.00032	0.00017
7.85	0.29	7.85	0.29	0.00023	0.00036
6.36	0.29	6.36	0.29	0.00138	0.00119
5.53	0.33	5.53	0.33	0.00137	0.00123
2.74	0.38	2.74	0.38	0.00383	0.00188



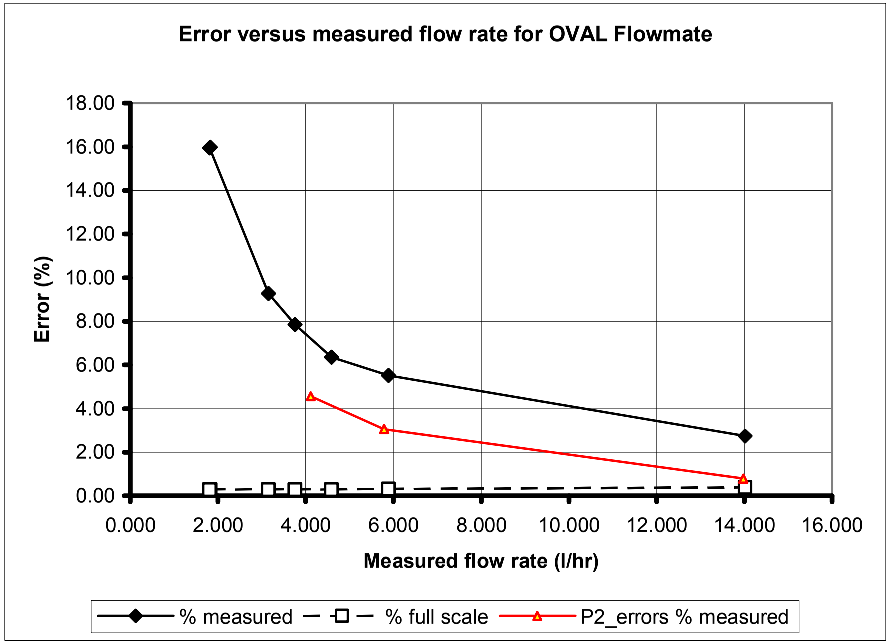


Table 13: "Recalibrated" performance of the Oval Flowmate MIII fuel flow meter, repetition 3

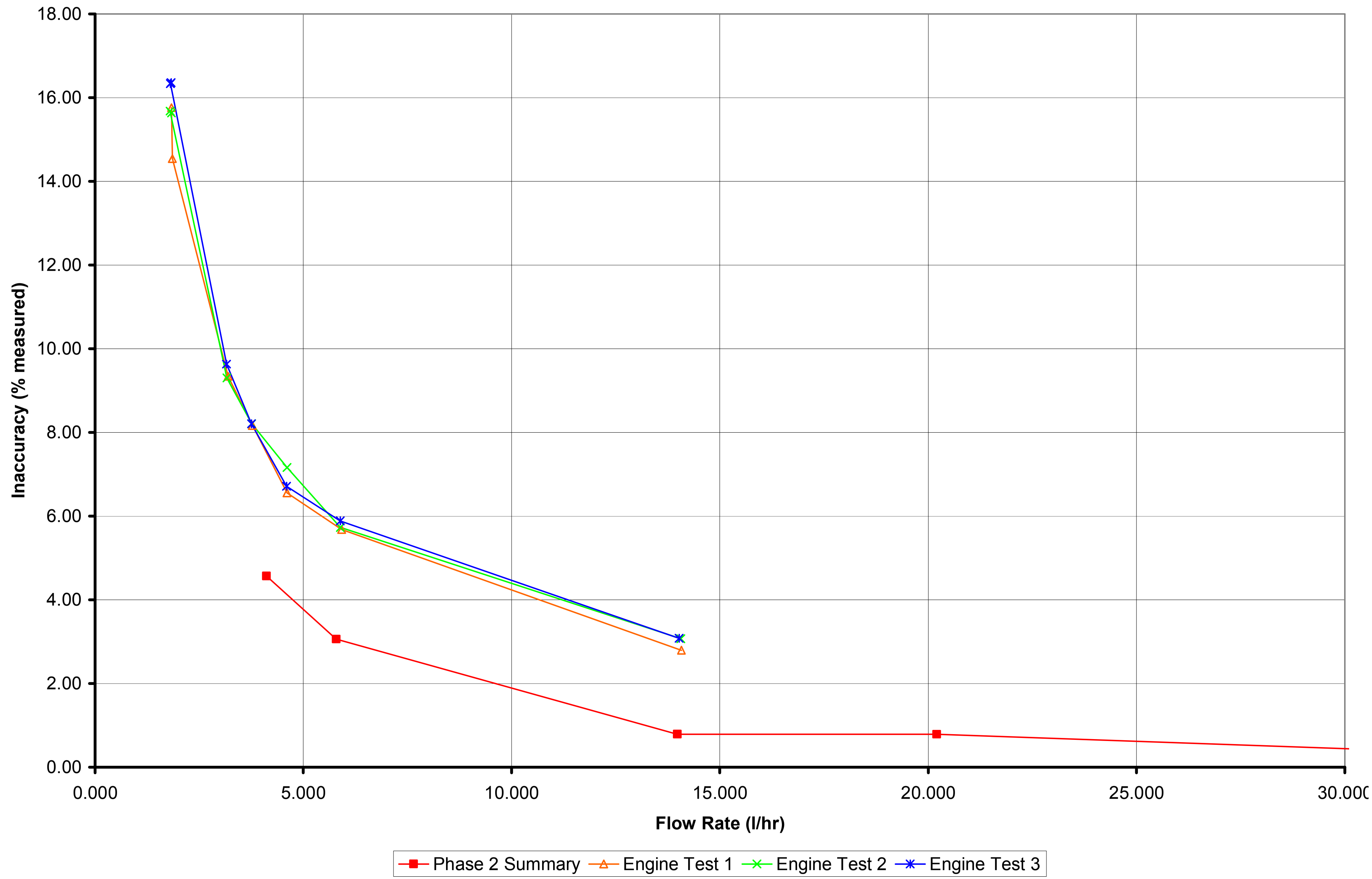


Figure 10: Accuracy versus flowrate for Oval Flowmate MIII fuel flow meter – "out-of-the-box"

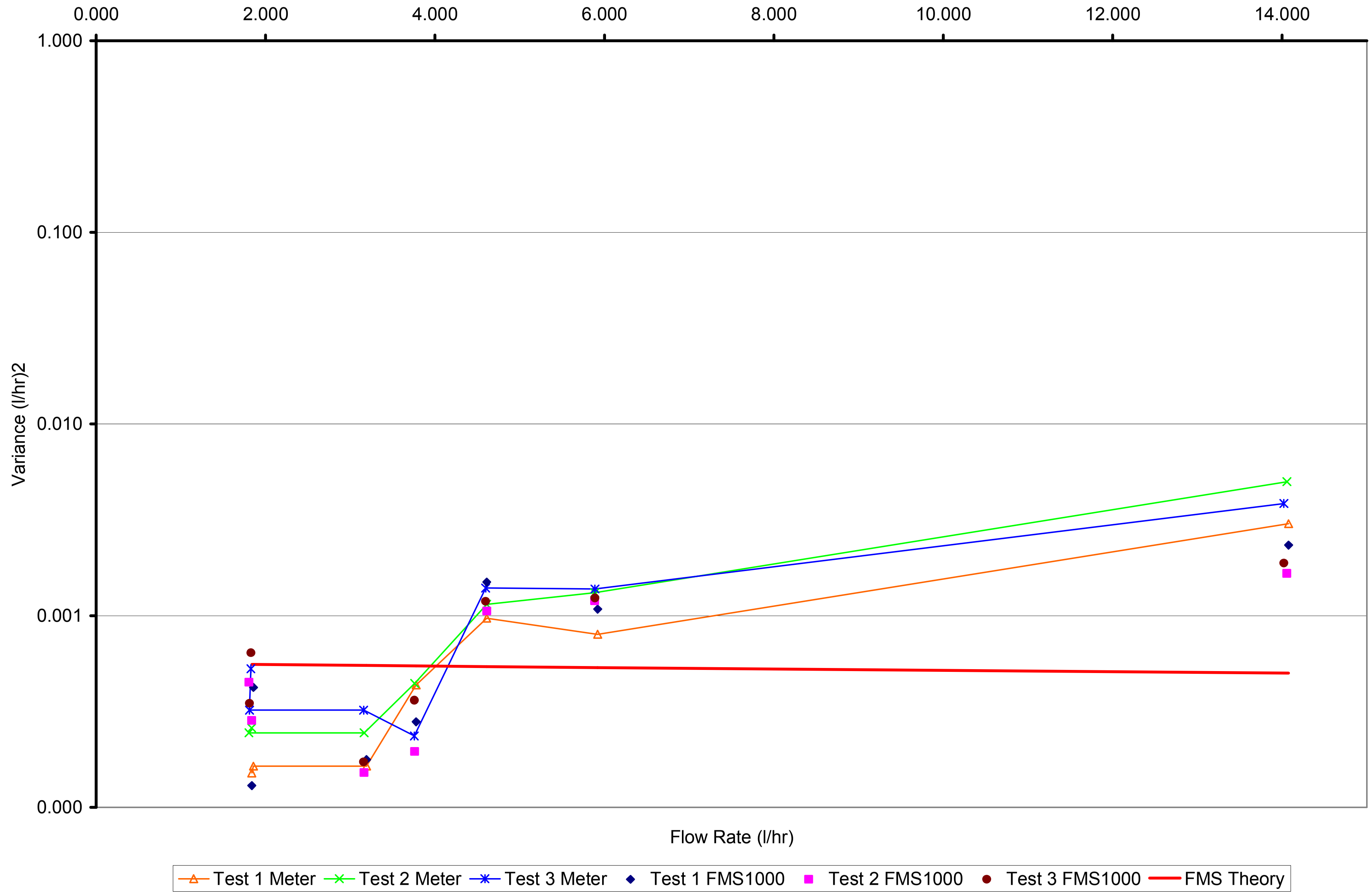


Figure 11: Variance versus flowrate for Oval Flowmate MIII fuel flow meter – "out-of-the-box"

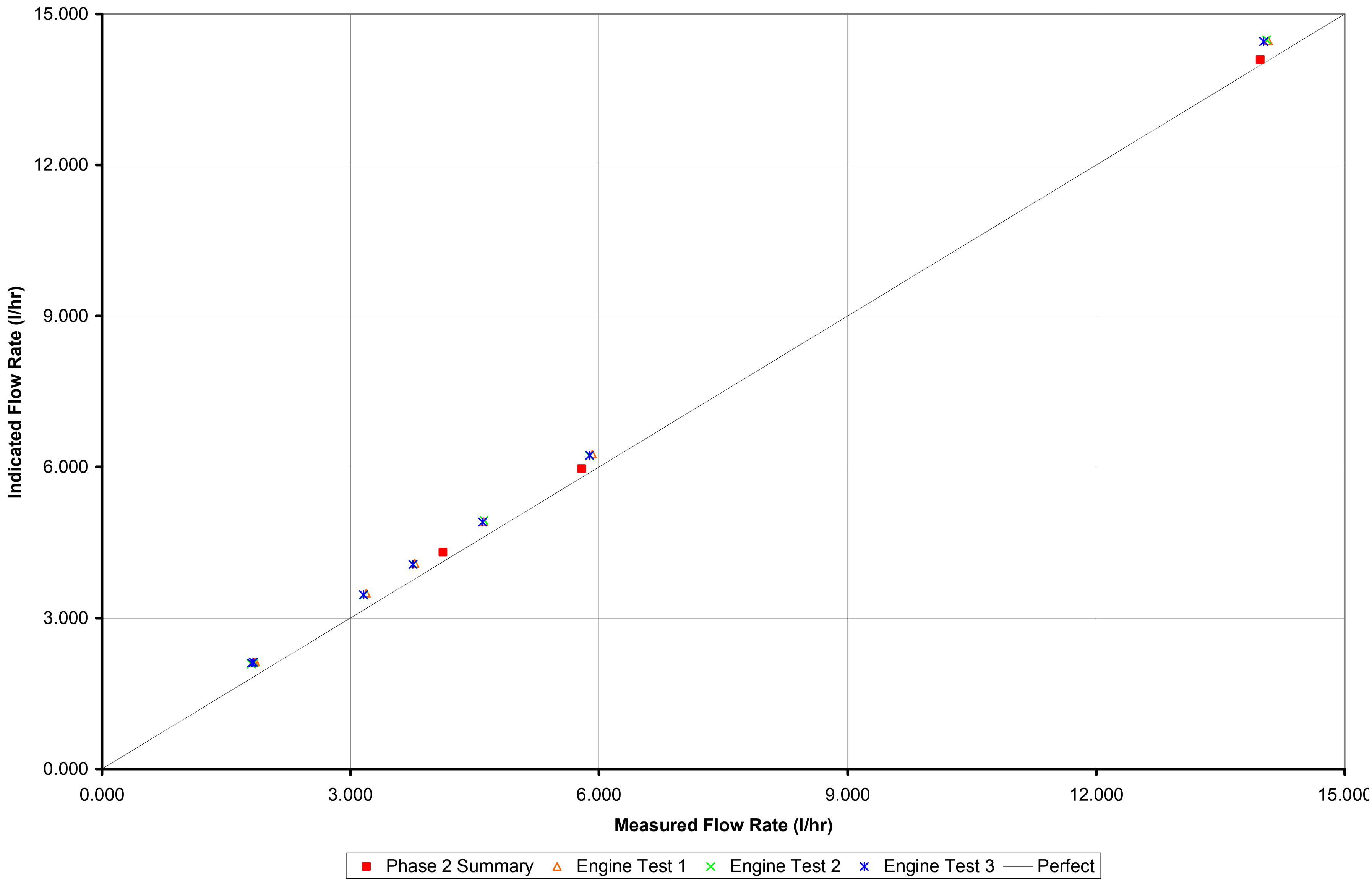


Figure 12: Indicated versus measured flowrate for Oval Flowmate MIII fuel flow meter – "out-of-the-box"

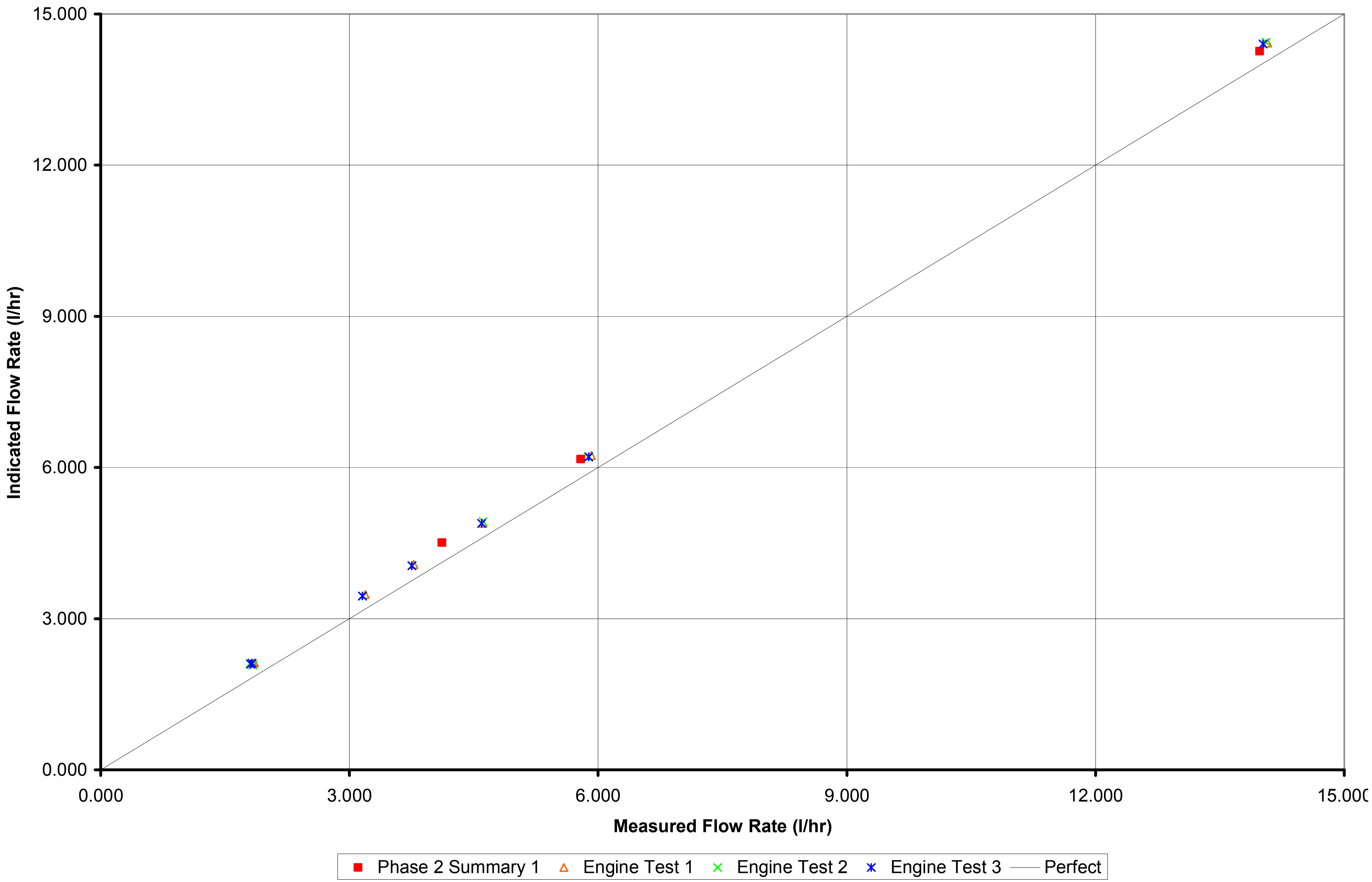
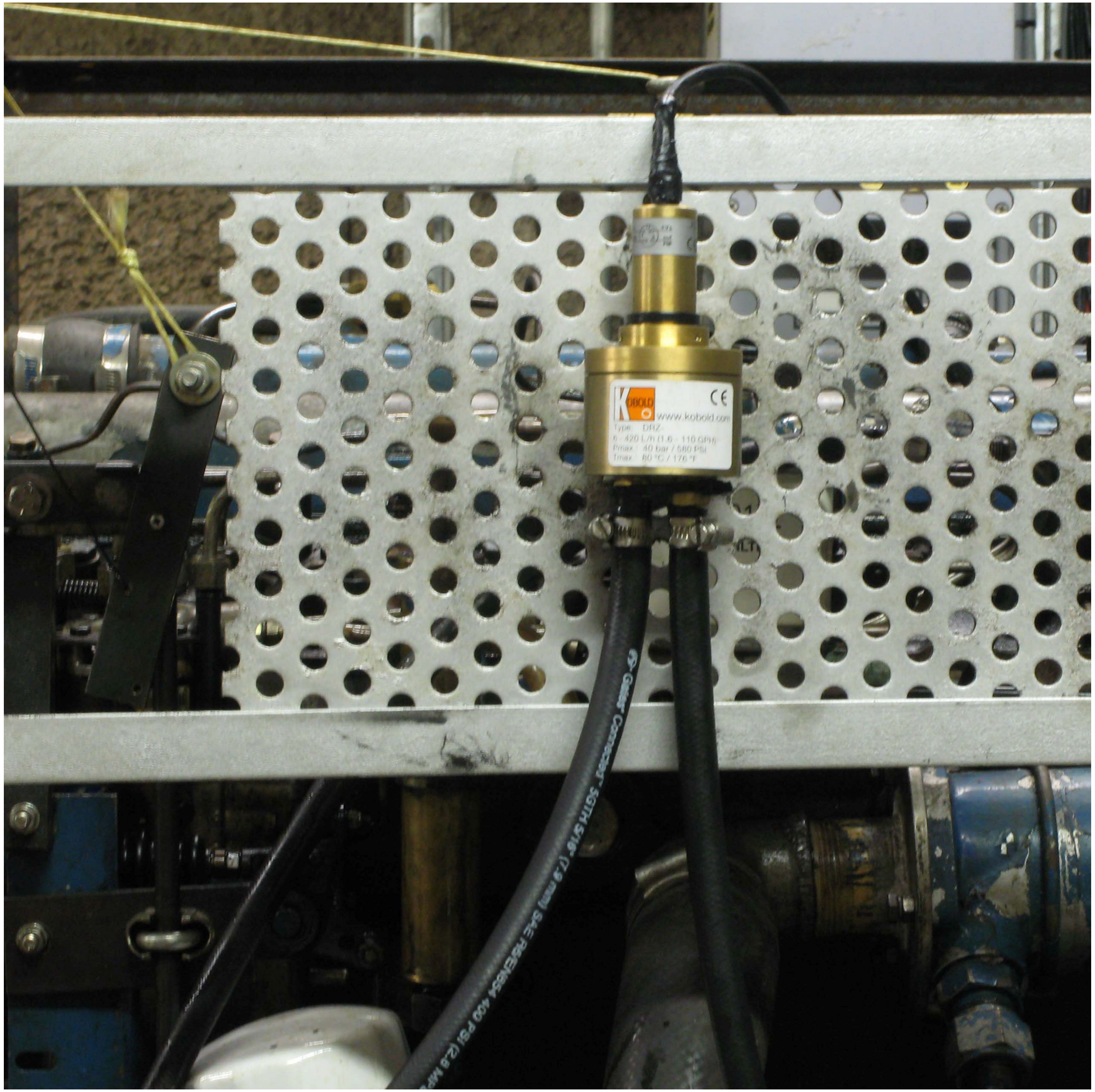


Figure 13: Indicated versus measured flowrate for Oval Flowmate MIII fuel flow meter – after Phase II calibration

Discussion

As before, the OVAL MIII Flowmate has fewer outliers than the M1, and is too close for our equipment to judge between them. It consistently performs within specification, under engine conditions, and, again, we cannot prove that being on an engine adversely affects this device at all.

Kobold DRZ Results

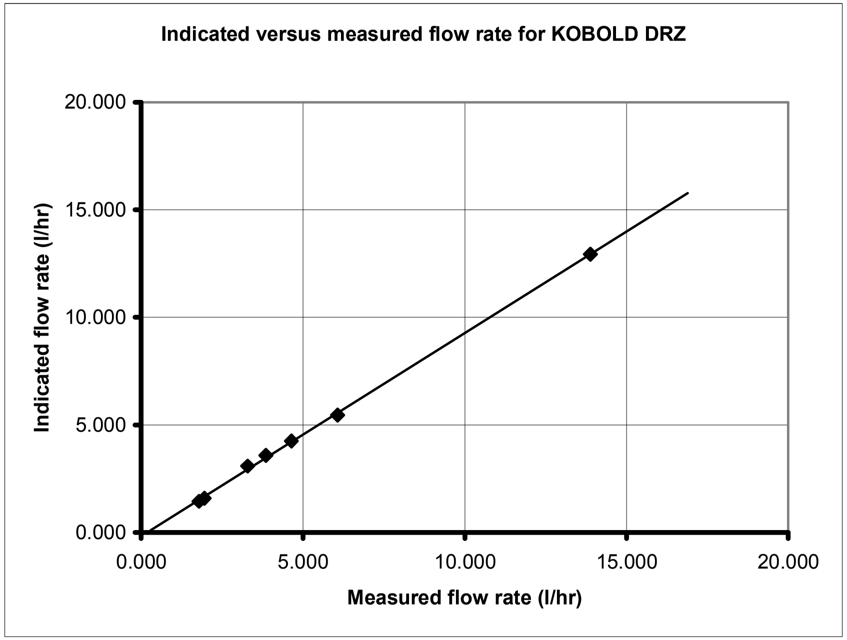


Engine Flow Summary 1

KOBOLD DRZ

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l
Idle	2.0	1.788	1.456	0.109	0.089
Idle	2.0	1.951	1.599	0.119	0.098
Gentle Cruise	2.5	3.295	3.090	0.201	0.189
Cruise & Shoot	3.8	3.854	3.578	0.236	0.219
Haul	4.6	4.641	4.258	0.284	0.260
Steam	5.9	6.065	5.452	0.371	0.333
Trawl	13.9	13.891	12.935	0.849	0.790

Inaccuracy in Indicated Flow Rate		Inaccuracy in Indicated Cumulative Volume		Variance of Indicated Flow	Variance of Measured Flow
% measured	% full scale	% measured	% full scale	$(l/hr)^2$	$(l/hr)^2$
-18.55	-0.08	-18.55	-0.08	0.00532	0.00082
-18.02	-0.08	-18.01	-0.08	0.00029	0.00019
-6.23	-0.05	-6.23	-0.05	0.00029	0.00041
-7.17	-0.07	-7.17	-0.07	0.00027	0.00026
-8.25	-0.09	-8.25	-0.09	0.00049	0.00092
-10.11	-0.15	-10.11	-0.15	0.00251	0.00206
-6.88	-0.23	-6.88	-0.23	0.00473	0.00217



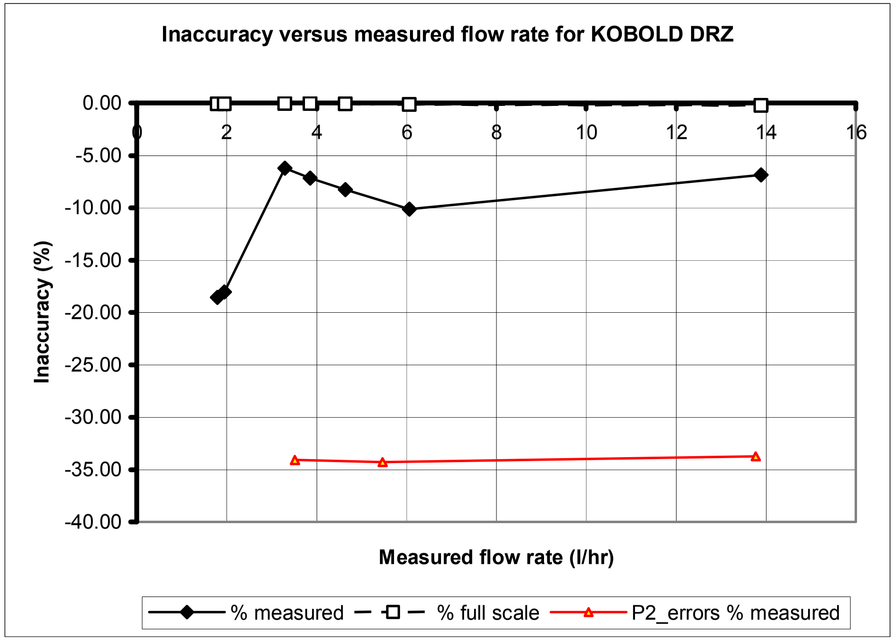


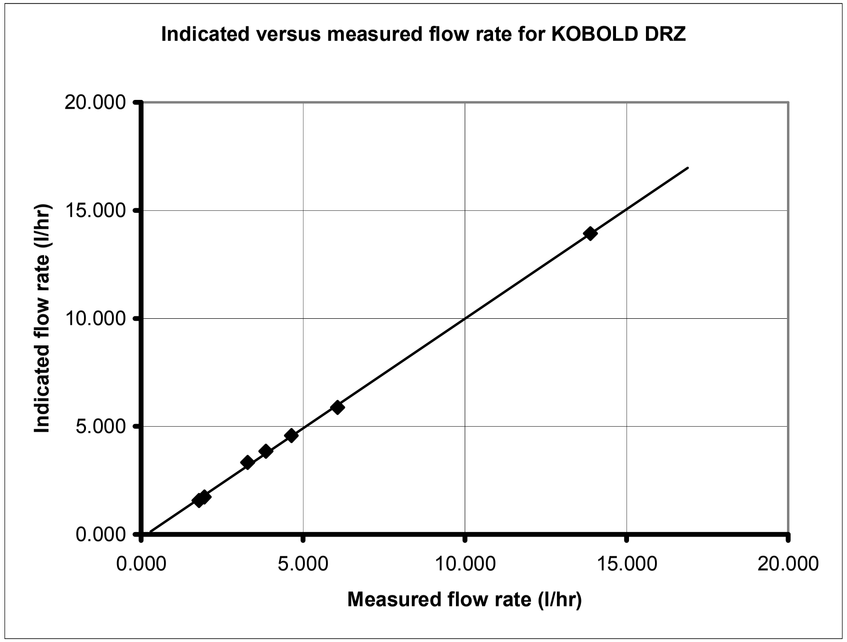
Table 14: "Out-of-the-box" performance of the Kobold DRZ fuel flow meter, repetition 1

Recalibrated

Engine Flow Summary

KOBOLD DRZ

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l	Inaccuracy in Indicated Flow Rate % measured	Inaccuracy in Indicated Flow Rate % full scale	Inaccuracy in Indicated Cumulative Volume % measured	Inaccuracy in Indicated Cumulative Volume % full scale	Variance of Indicated Flow $(l/hr)^2$	Variance of Measured Flow $(l/hr)^2$
Idle	2.0	1.788	1.569	0.109	0.096	-12.25	-0.05	-12.25	-0.05	0.00618	0.00082
Idle	2.0	1.951	1.723	0.119	0.105	-11.68	-0.05	-11.67	-0.05	0.00034	0.00019
Gentle Cruise	2.5	3.295	3.329	0.201	0.203	1.02	0.01	1.02	0.01	0.00034	0.00041
Cruise & Shoot	3.8	3.854	3.854	0.236	0.236	0.01	0.00	0.01	0.00	0.00031	0.00026
Haul	4.6	4.641	4.587	0.284	0.280	-1.15	-0.01	-1.15	-0.01	0.00057	0.00092
Steam	5.9	6.065	5.874	0.371	0.359	-3.16	-0.05	-3.16	-0.05	0.00291	0.00206
Trawl	13.9	13.891	13.935	0.849	0.852	0.32	0.01	0.32	0.01	0.00549	0.00217



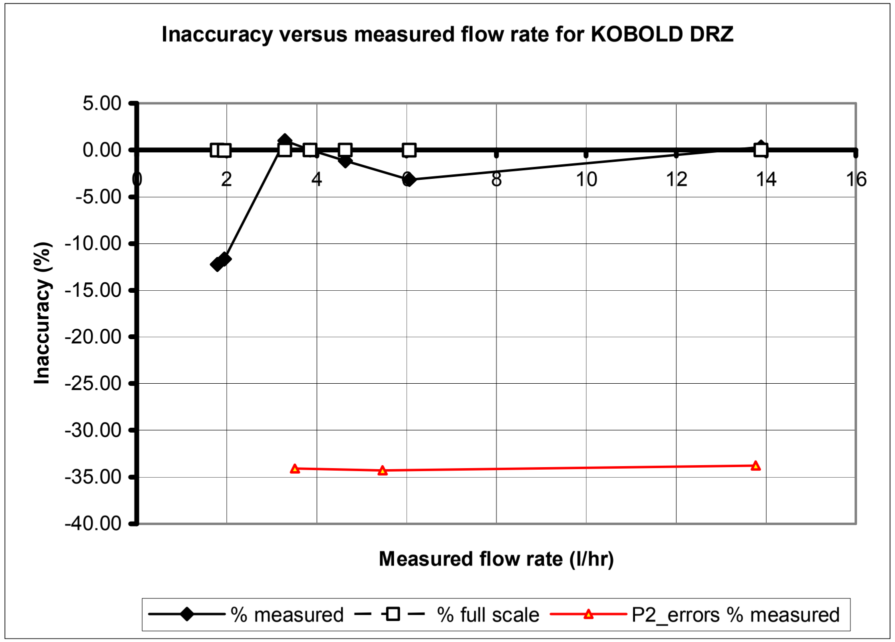


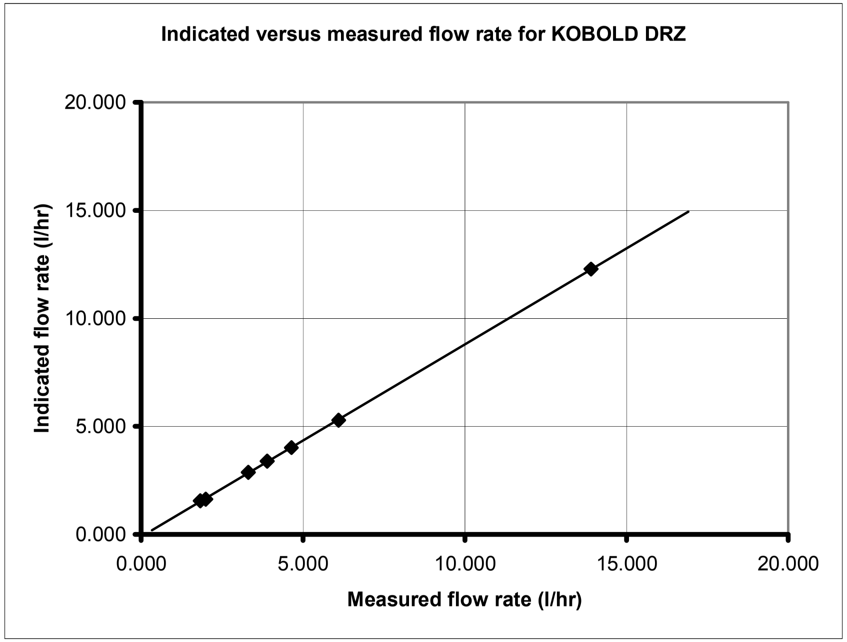
Table 15: “Recalibrated” performance of the Kobold DRZ fuel flow meter, repetition 1

Engine Flow Summary 2

KOBOLD DRZ

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l
Idle	2.0	1.830	1.566	0.112	0.096
Idle	2.0	1.995	1.636	0.122	0.100
Gentle Cruise	2.5	3.314	2.871	0.203	0.175
Cruise & Shoot	3.8	3.889	3.388	0.238	0.207
Haul	4.6	4.637	4.015	0.283	0.245
Steam	5.9	6.106	5.286	0.374	0.323
Trawl	13.9	13.904	12.287	0.851	0.751

Inaccuracy in Indicated Flow Rate		Inaccuracy in Indicated Cumulative Volume		Variance of Indicated Flow	Variance of Measured Flow
% measured	% full scale	% measured	% full scale	$(l/hr)^2$	$(l/hr)^2$
-14.45	-0.06	-14.45	-0.06	0.00023	0.00030
-18.00	-0.09	-18.00	-0.09	0.00019	0.00018
-13.35	-0.11	-13.35	-0.11	0.00019	0.00066
-12.89	-0.12	-12.89	-0.12	0.00026	0.00029
-13.41	-0.15	-13.41	-0.15	0.00082	0.00108
-13.43	-0.20	-13.61	-0.20	0.00138	0.00268
-11.63	-0.38	-11.72	-0.39	0.00385	0.00270



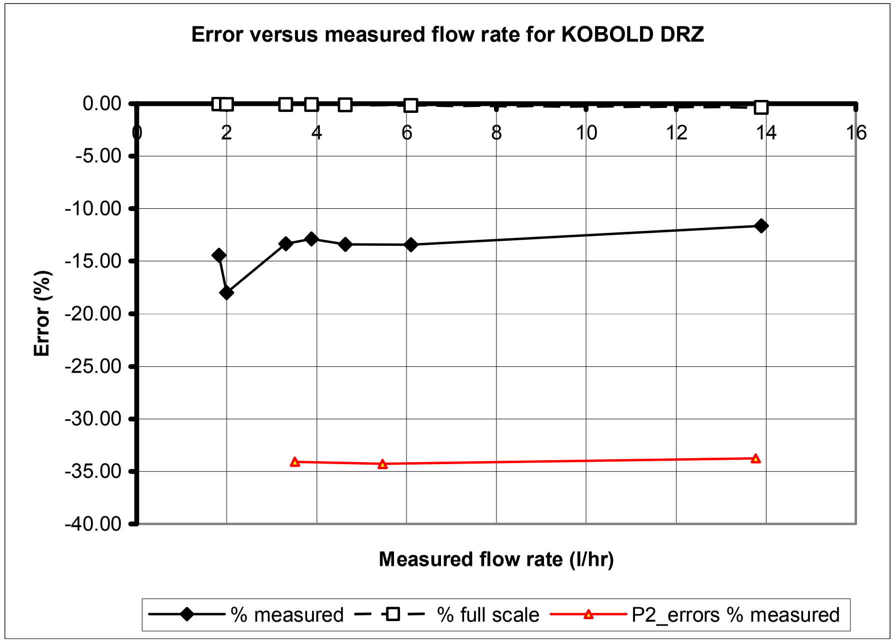


Table 16: "Out-of-the-box" performance of the Kobold DRZ fuel flow meter, repetition 2

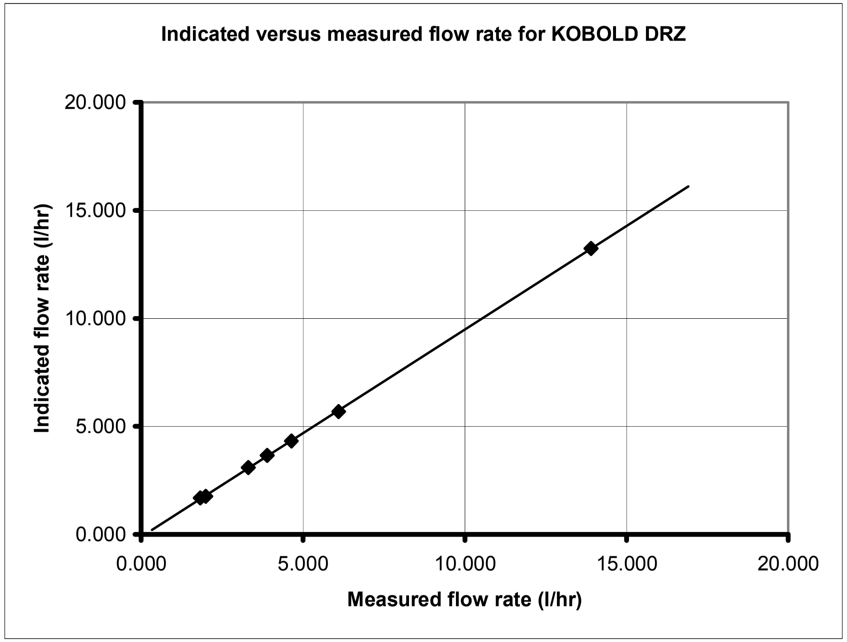
Recalibrated

Engine Flow Summary 2

KOBOLD DRZ

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l
Idle	2.0	1.830	1.687	0.112	0.103
Idle	2.0	1.995	1.762	0.122	0.108
Gentle Cruise	2.5	3.314	3.093	0.203	0.189
Trawl	13.9	3.889	3.650	0.238	0.223
Haul	4.6	4.637	4.325	0.283	0.264
Steam	5.9	6.106	5.695	0.374	0.348
Trawl	13.9	13.904	13.237	0.851	0.809

Inaccuracy in Indicated Flow Rate		Inaccuracy in Indicated Cumulative Volume		Variance of Indicated Flow	Variance of Measured Flow
% measured	% full scale	% measured	% full scale	$(l/hr)^2$	$(l/hr)^2$
-7.84	-0.03	-7.84	-0.03	0.00027	0.00030
-11.66	-0.06	-11.66	-0.06	0.00023	0.00018
-6.65	-0.05	-6.65	-0.05	0.00023	0.00066
-6.15	-0.06	-6.15	-0.06	0.00031	0.00029
-6.72	-0.07	-6.72	-0.07	0.00096	0.00108
-6.73	-0.10	-6.93	-0.10	0.00161	0.00268
-4.79	-0.16	-4.89	-0.16	0.00447	0.00270



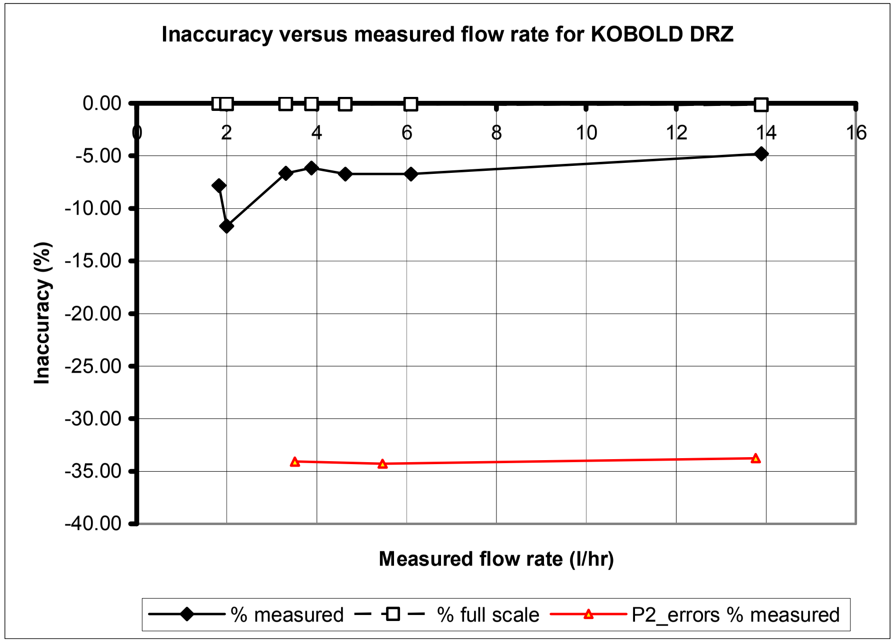


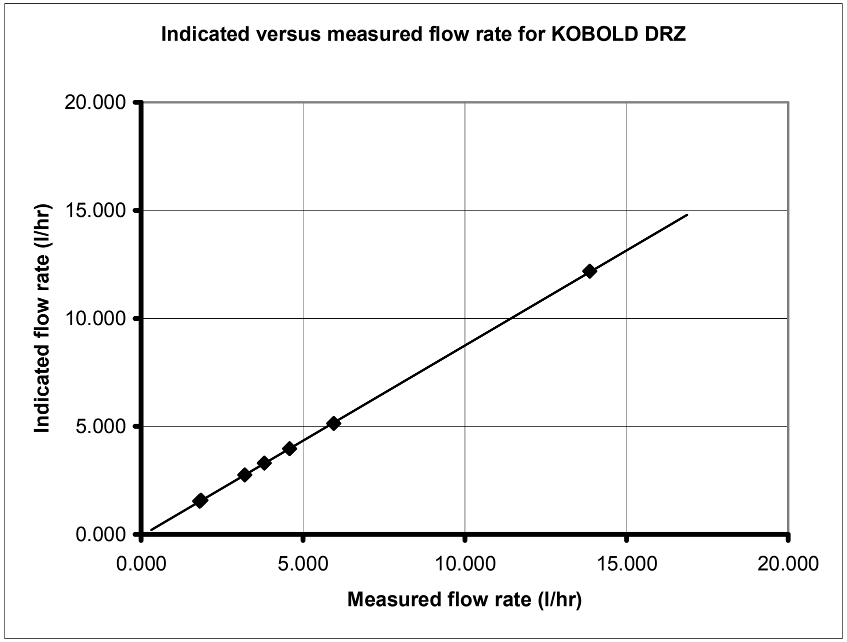
Table 17: "Recalibrated" performance of the Kobold DRZ fuel flow meter, repetition 2

Engine Flow Summary 3

KOBOLD DRZ

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l
Idle	2.0	1.805	1.550	0.110	0.095
Idle	2.0	1.844	1.585	0.113	0.097
Gentle Cruise	2.5	3.194	2.755	0.195	0.168
Cruise & Shoot	3.8	3.811	3.297	0.233	0.201
Haul	4.6	4.588	3.962	0.280	0.242
Steam	5.9	5.956	5.146	0.364	0.314
Trawl	13.9	13.867	12.181	0.847	0.744

Inaccuracy in Indicated Flow Rate		Inaccuracy in Indicated Cumulative Volume		Variance of Indicated Flow $(l/hr)^2$	Variance of Measured Flow $(l/hr)^2$
% measured	% full scale	% measured	% full scale		
-14.12	-0.06	-14.12	-0.06	0.00030	0.00031
-14.03	-0.06	-14.03	-0.06	0.00013	0.00020
-13.75	-0.10	-13.75	-0.10	0.00013	0.00026
-13.47	-0.12	-13.47	-0.12	0.00022	0.00018
-13.64	-0.15	-13.64	-0.15	0.00125	0.00132
-13.60	-0.19	-13.60	-0.19	0.00078	0.00107
-12.16	-0.40	-12.16	-0.40	0.00249	0.00218



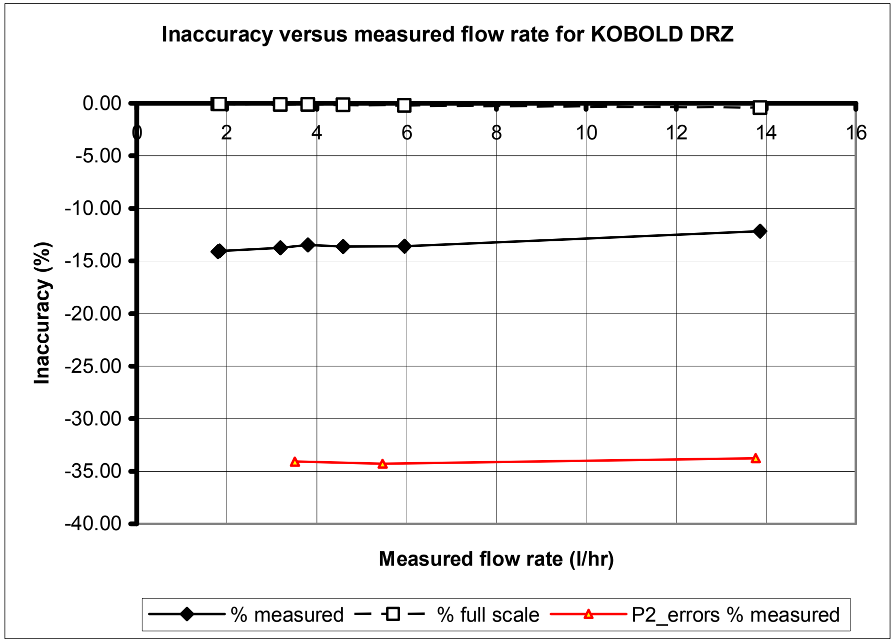
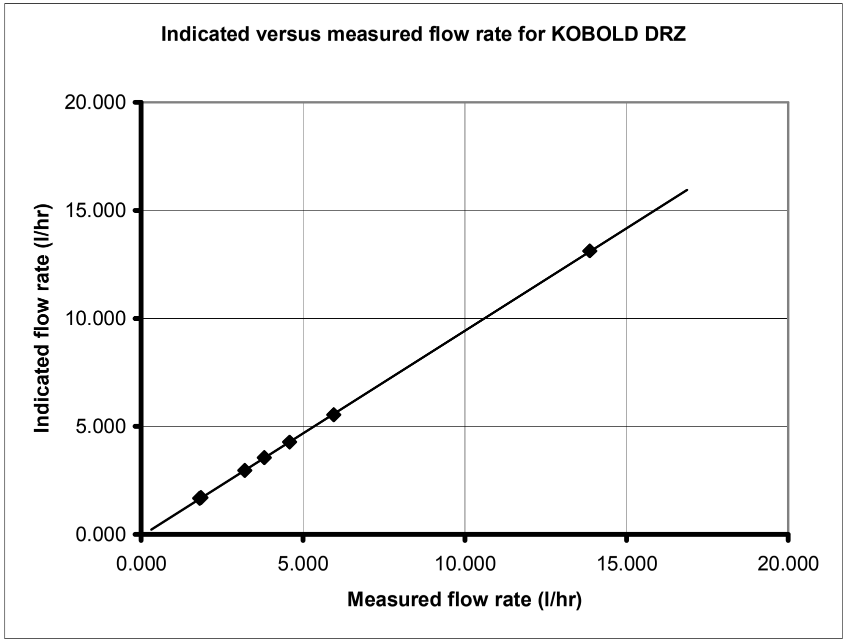


Table 18: "Out-of-the-box" performance of the Kobold DRZ fuel flow meter, repetition 3

Recalibrated **Engine Flow Summary** KOBOLD DRZ

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l
Idle	2.0	1.805	1.670	0.110	0.102
Idle	2.0	1.844	1.708	0.113	0.104
Gentle Cruise	2.5	3.194	2.968	0.195	0.181
Cruise & Shoot	3.8	3.811	3.552	0.233	0.217
Haul	4.6	4.588	4.268	0.280	0.261
Steam	5.9	5.956	5.544	0.364	0.339
Trawl	13.9	13.867	13.123	0.847	0.802

Inaccuracy in Indicated Flow Rate		Inaccuracy in Indicated Cumulative Volume		Variance of Indicated Flow	Variance of Measured Flow
% measured	% full scale	% measured	% full scale	$(l/hr)^2$	$(l/hr)^2$
-7.48	-0.03	-7.48	-0.03	0.00035	0.00031
-7.39	-0.03	-7.39	-0.03	0.00015	0.00020
-7.08	-0.05	-7.08	-0.05	0.00015	0.00026
-6.78	-0.06	-6.78	-0.06	0.00026	0.00018
-6.96	-0.08	-6.96	-0.08	0.00146	0.00132
-6.92	-0.10	-6.92	-0.10	0.00091	0.00107
-5.37	-0.18	-5.37	-0.18	0.00289	0.00218



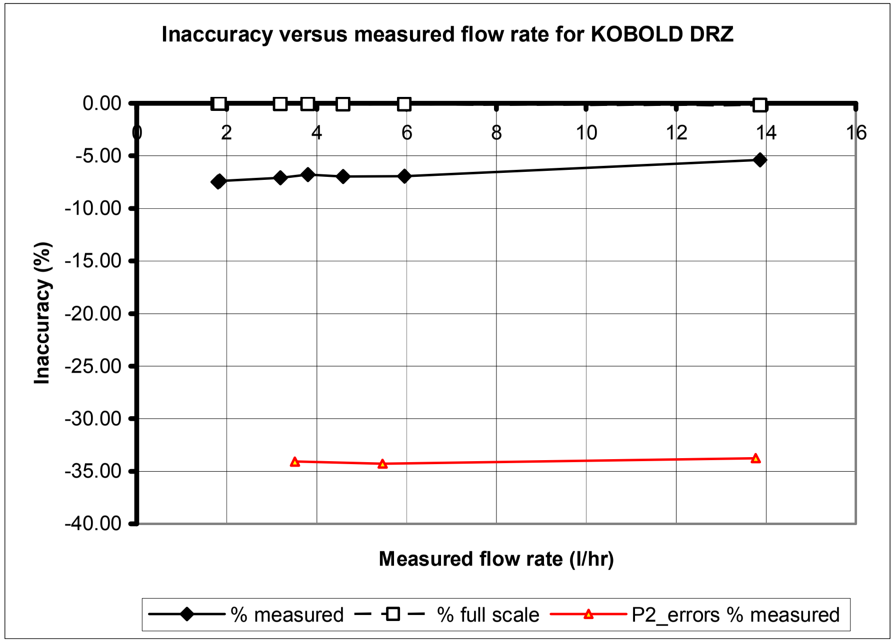


Table 19: "Recalibrated" performance of the Kobold DRZ fuel flow meter, repetition 3

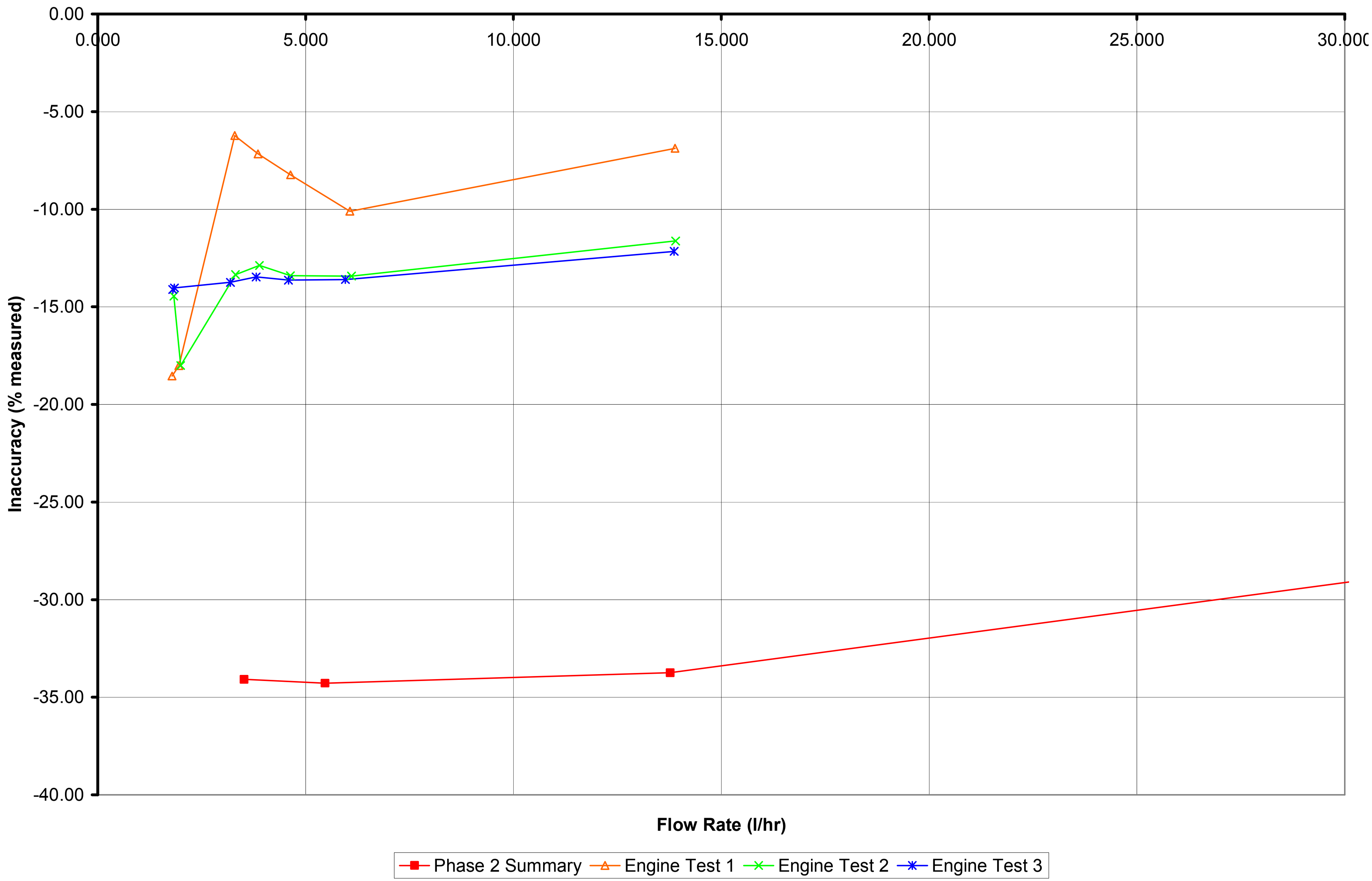


Figure 14: Accuracy versus flowrate for Kobold DRZ fuel flow meter – "out-of-the-box"

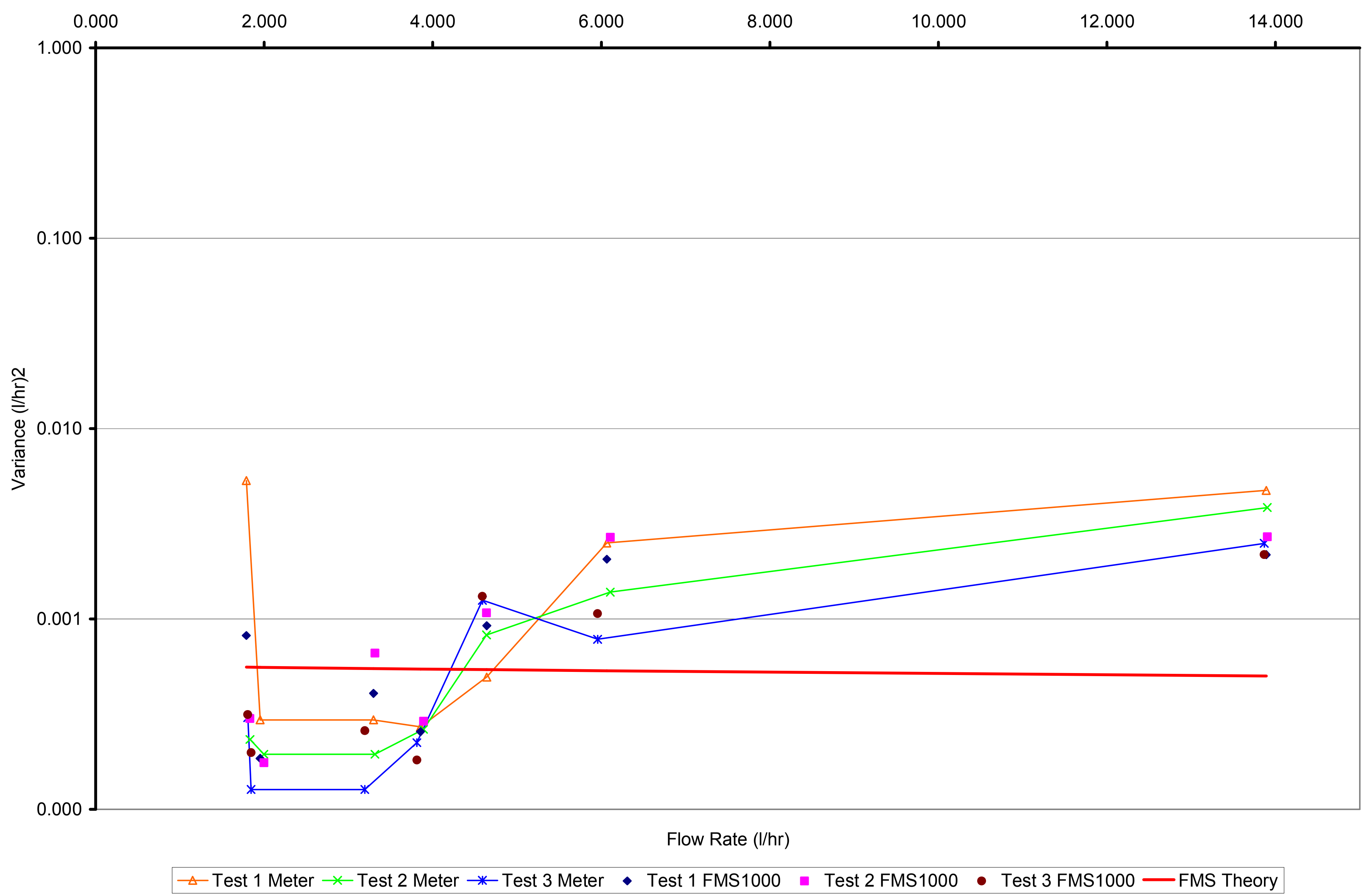


Figure 15: Variance versus flowrate for Kobold DRZ fuel flow meter – “out-of-the-box”

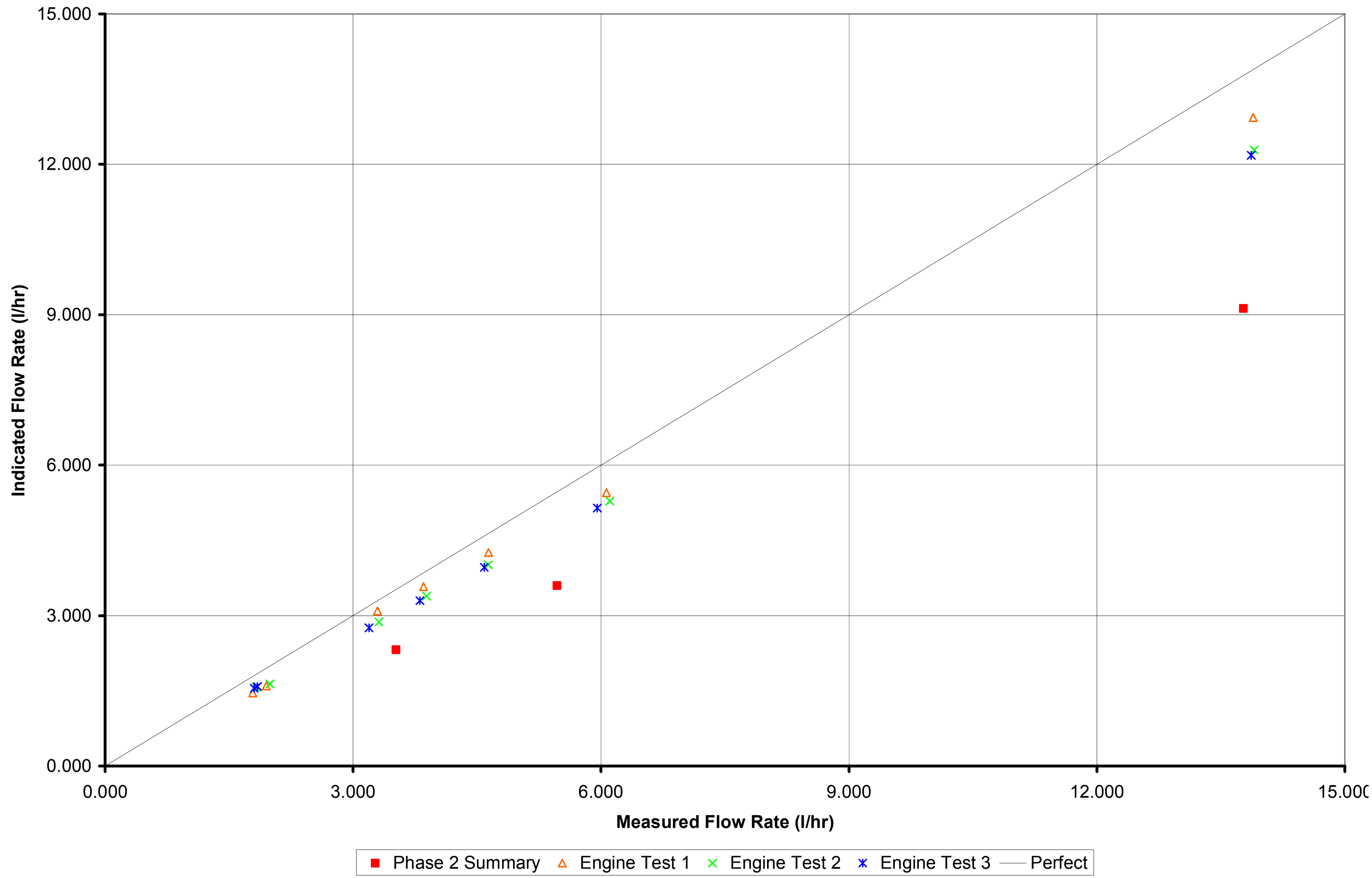


Figure 16: Indicated versus measured flowrate for Kobold DRZ fuel flow meter – “out-of-the-box”

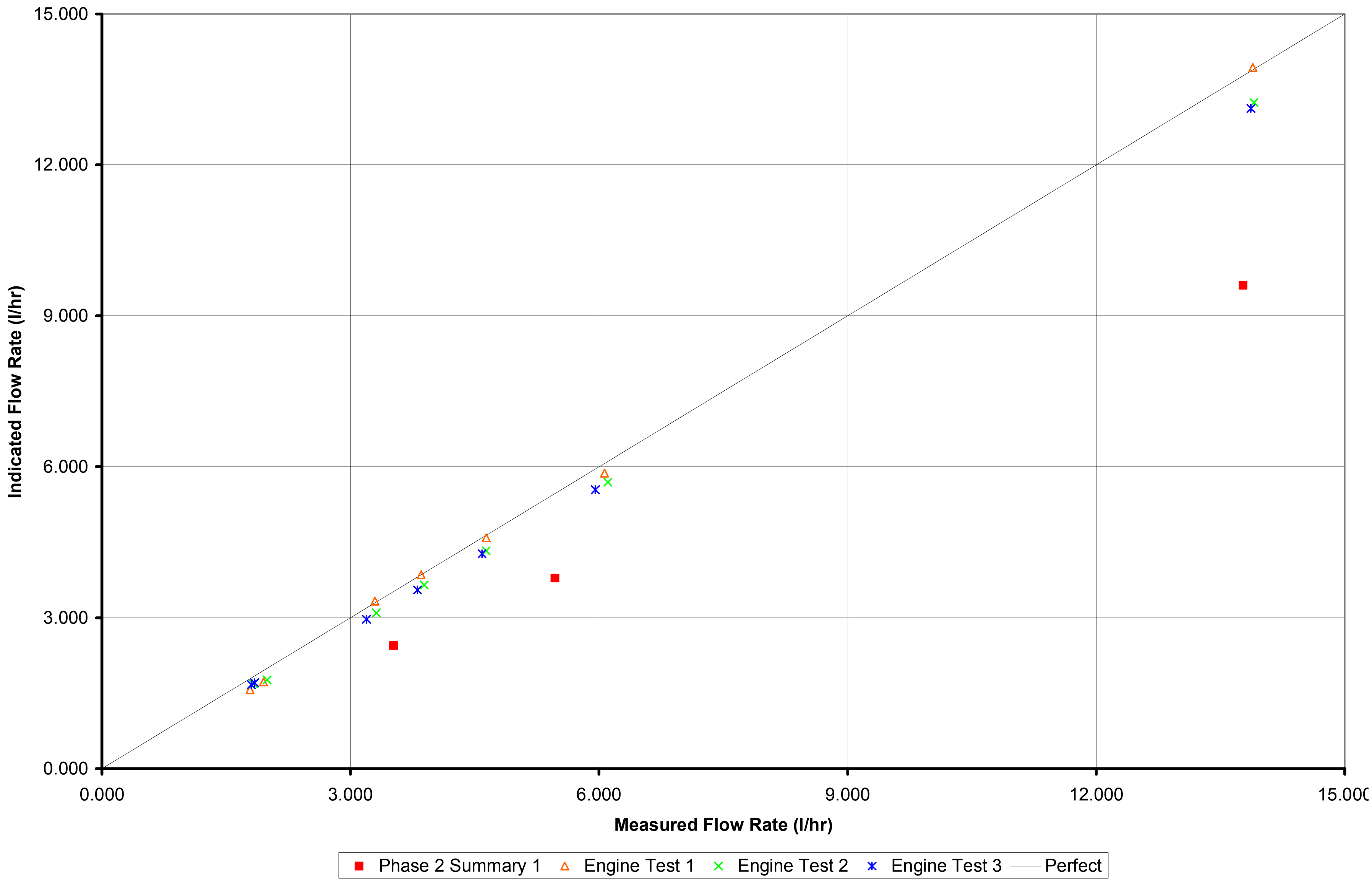


Figure 17: Indicated versus measured flowrate for Kobold DRZ fuel flow meter – after Phase II calibration

Discussion

For the Kobold DRZ, after the Phase II report was submitted, the voltage output from the Data Track 284 was re-ranged to be more compatible with the full scale flow rate of this device (which is much higher than the other devices), and the Phase II testing re-done. Prior to this adjustment, due to channel voltage settings, the data from this device was logged with an uncertainty of ± 1l/hr meaning that a 20% inaccuracy at 5 l/hr could be accounted for by our equipment. After the re-ranging of the Data Track 284 output voltage from this device, it was logged with an uncertainty of ± 0.17 l/hr. The Phase II results for this device shown in Tables 14 to 19 and Figures 14 to 17 are for these repeat tests.

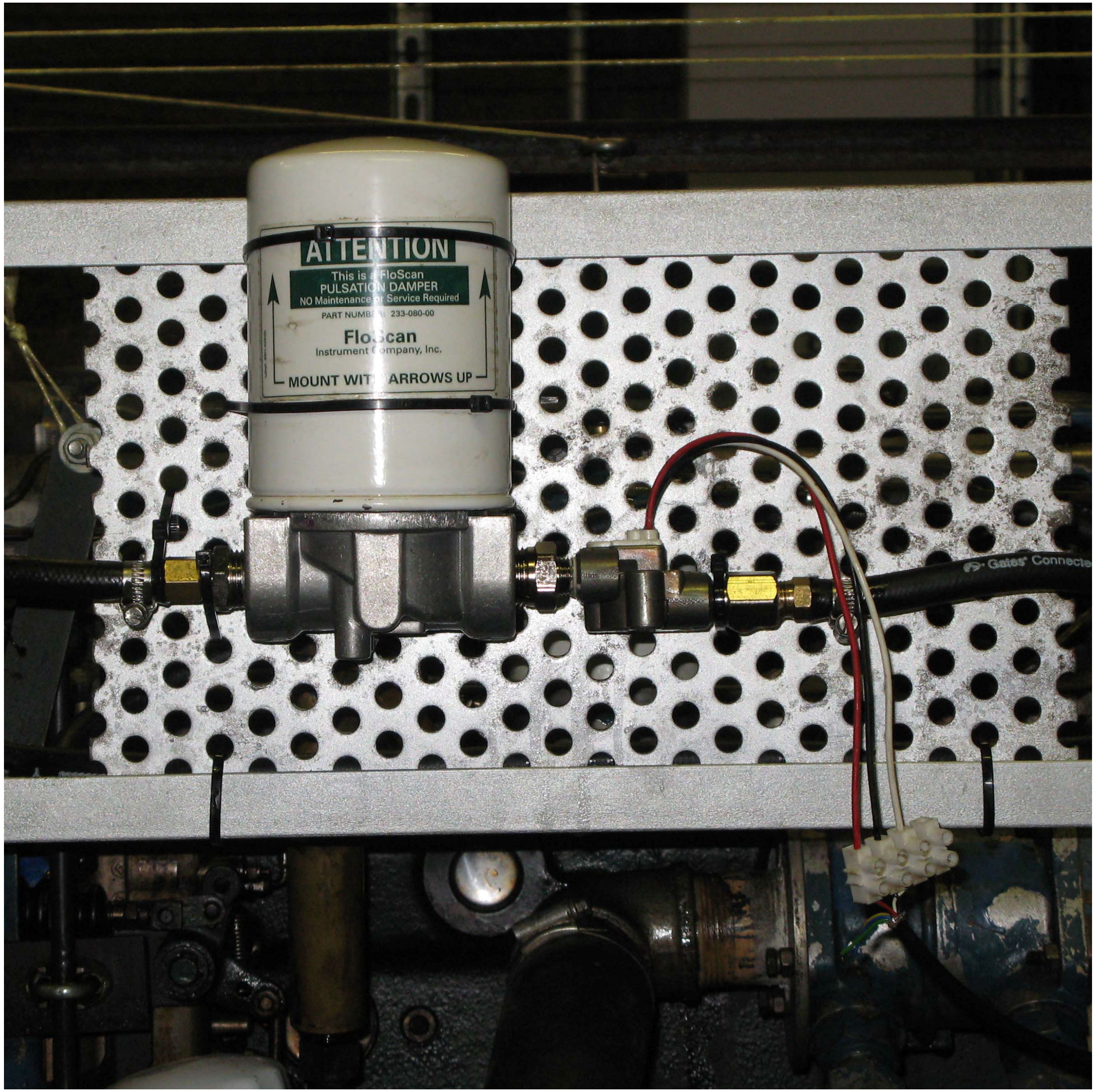
With an "out-of-the-box" accuracy of 34.09% at the lowest (most demanding) flow rate in the Phase II (expressed as a percentage of the observation), the results still do not indicate a particularly satisfactory performance of the meter. The same is true when comparing the accuracy expressed as a percentage of the full scale flow rate (although the Kobold DRZ has an advantage here compared with the other meters, of having a much higher full scale flow rate).

The real surprise provided by the Kobold DRZ comes when the results of the Phase III testing are considered. "Out-of-the-box" accuracy expressed as a percentage of the observation at ~4.6 l/h is –8.25% to –13.64%, representing consistent under reading, but a much improved performance in comparison to the Phase II performance. After calibration (using the Phase II calibration parameters), the accuracy, expressed as a percentage of the observation falls to between –1.55% to –6.96%, which moves this device into first place on this key measure of performance, in comparison to the other devices. Another interesting observation regarding this device is that the accuracy of the device seems to be more-or-less constant with flow rate, both for Phase II and Phase III tests; this device should calibrate well in operational environments to produce very accurate measurements.

Figure 15 shows that, on the engine, the repeatability of this device is also excellent, being comparable with that of the FMS under these testing conditions.

The puzzle with this particular fuel meter is thus why did it perform so poorly in the Phase II testing when it has performed so well under the Phase III tests?

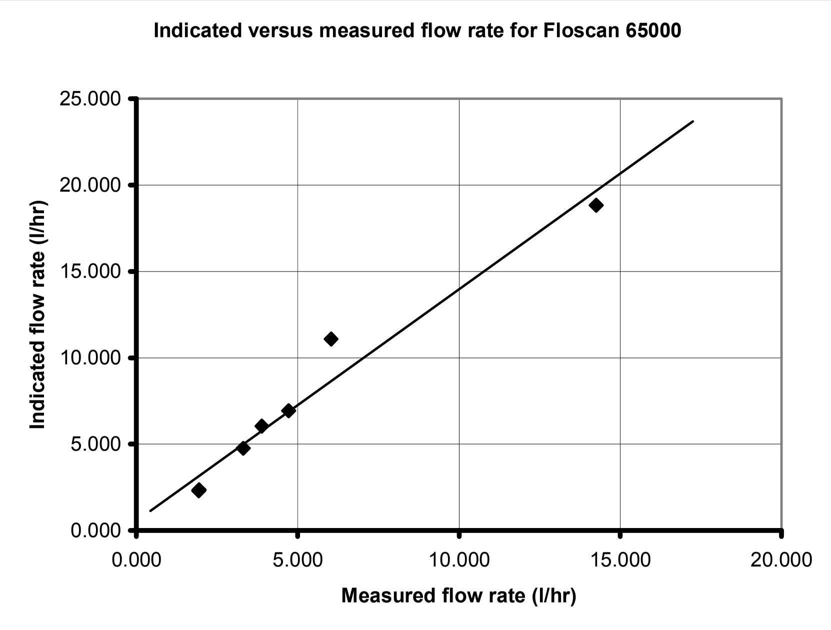
Floscan Cruisemaster 65000 Results



Engine Flow Summary 1

Floscan 65000

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l	Inaccuracy in Indicated Flow Rate % measured	Inaccuracy in Indicated Flow Rate % full scale	Inaccuracy in Indicated Cumulative Volume % measured	Inaccuracy in Indicated Cumulative Volume % full scale	Variance of Indicated Flow $(l/hr)^2$	Variance of Measured Flow $(l/hr)^2$
Idle	2.0	1.948	2.354	0.119	0.144	20.82	1.01	20.81	1.01	0.02067	0.00056
Idle	2.0	1.933	2.294	0.118	0.140	18.67	0.90	18.70	0.90	0.00813	0.00018
Gentle Cruise	2.5	3.309	4.753	0.202	0.290	43.64	3.61	43.64	3.61	0.00813	0.00033
Cruise & Shoot	3.8	3.888	6.040	0.238	0.369	55.34	5.38	55.34	5.38	0.01751	0.00051
Haul	4.6	4.719	6.939	0.288	0.424	47.05	5.55	47.04	5.55	0.01036	0.00120
Steam	5.9	6.038	11.092	0.369	0.678	83.71	12.64	83.70	12.63	0.01751	0.00185
Trawl	13.9	14.254	18.829	0.871	1.151	32.10	11.44	32.09	11.44	0.03424	0.00221



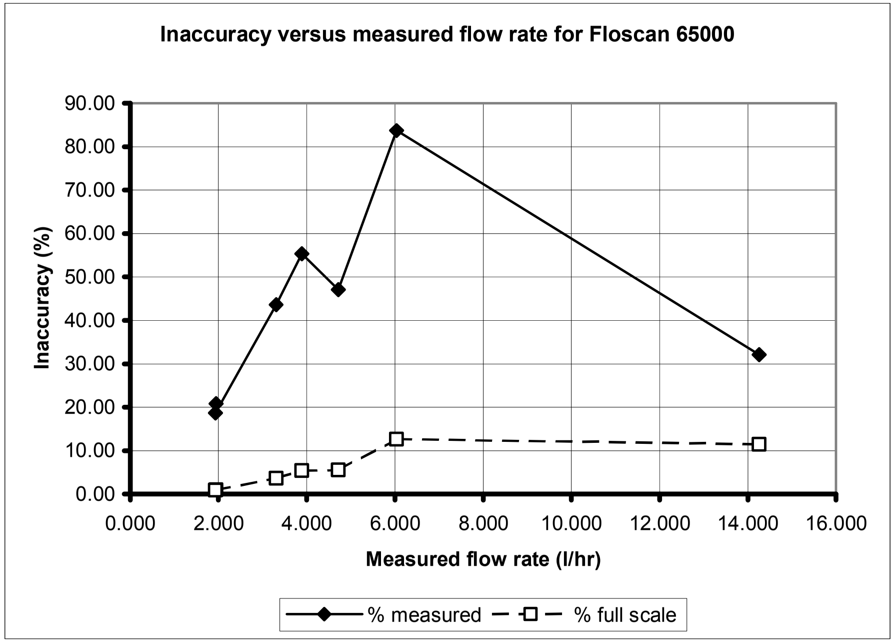


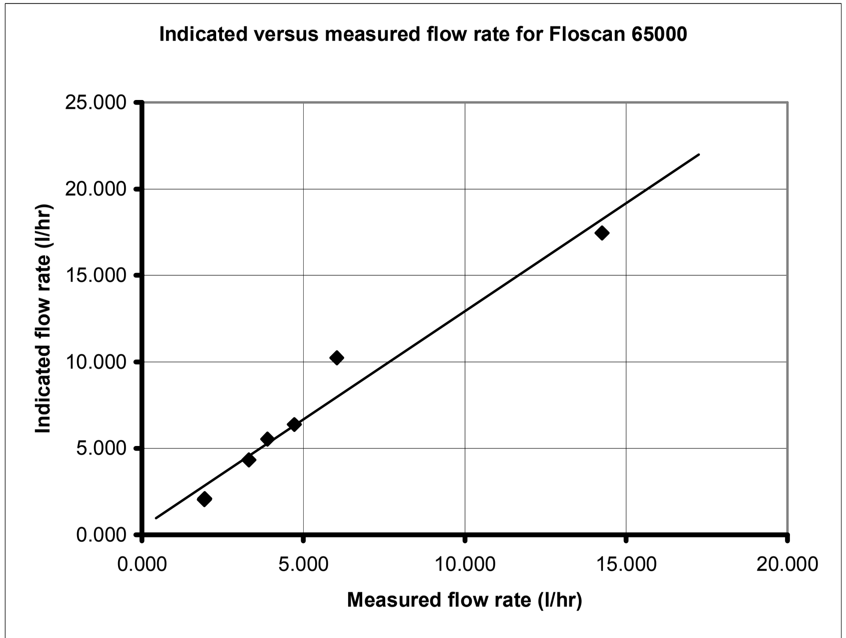
Table 20: "Out-of-the-box" performance of the Floscan Cruisemaster 65000 fuel flow meter, repetition 1

Recalibrated

Engine Flow Summary 1

Floscan 65000

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l	Inaccuracy in Indicated Flow Rate % measured	Inaccuracy in Indicated Flow Rate % full scale	Inaccuracy in Indicated Cumulative Volume % measured	Inaccuracy in Indicated Cumulative Volume % full scale	Variance of Indicated Flow $(l/hr)^2$	Variance of Measured Flow $(l/hr)^2$
Idle	2.0	1.948	2.096	0.119	0.032	7.60	0.37	-73.10	-3.56	0.0180	0.00056
Idle	2.0	1.933	2.040	0.118	0.125	5.56	0.27	5.59	0.27	0.0200	0.00018
Gentle Cruise	2.5	3.309	4.333	0.202	0.066	30.95	2.56	-67.26	-5.56	0.0071	0.00033
Cruise & Shoot	3.8	3.888	5.534	0.238	0.085	42.31	4.11	-64.42	-6.26	0.0152	0.00051
Haul	4.6	4.719	6.371	0.288	0.097	35.02	4.13	-66.25	-7.81	0.0090	0.00120
Steam	5.9	6.038	10.244	0.369	0.157	69.66	10.51	-57.59	-8.69	0.0152	0.00185
Trawl	13.9	14.254	17.458	0.871	0.267	22.48	8.01	-69.38	-24.72	0.0298	0.00221



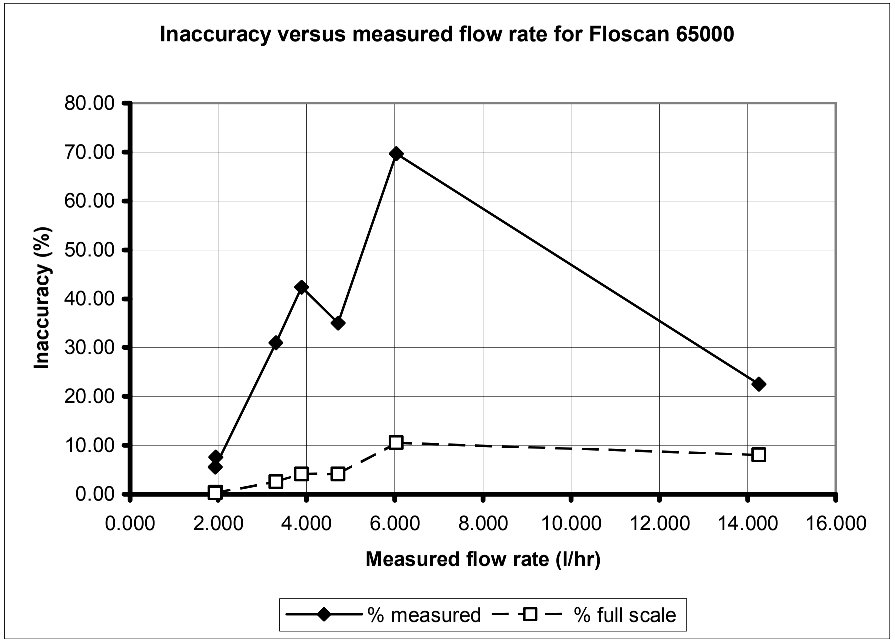


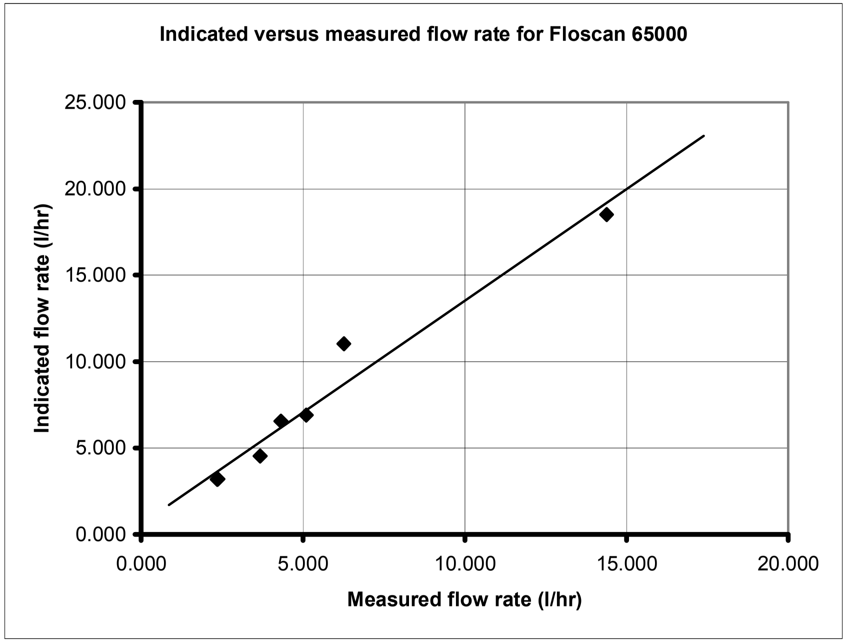
Table 21: "Recalibrated" performance of the Floscan Cruisemaster 65000 fuel flow meter, repetition 1

Engine Flow Summary 2

Floscan 65000

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l
Idle	2.0	2.354	3.177	0.144	0.194
Idle	2.0	2.376	3.193	0.145	0.195
Gentle Cruise	2.5	3.680	4.526	0.225	0.277
Cruise & Shoot	3.8	4.320	6.544	0.264	0.400
Haul	4.6	5.104	6.908	0.312	0.422
Steam	5.9	6.262	11.028	0.383	0.674
Trawl	13.9	14.387	18.521	0.879	1.132

Inaccuracy in Indicated Flow Rate		Inaccuracy in Indicated Cumulative Volume		Variance of Indicated Flow	Variance of Measured Flow
% measured	% full scale	% measured	% full scale	$(l/hr)^2$	$(l/hr)^2$
34.97	2.06	35.00	2.06	0.02457	0.00039
34.41	2.04	34.42	2.04	0.02173	0.00083
23.00	2.12	23.00	2.12	0.02173	0.00010
51.48	5.56	51.47	5.56	0.02607	0.00022
35.34	4.51	35.34	4.51	0.01389	0.00041
76.11	11.91	76.11	11.91	0.04740	0.00686
28.73	10.33	28.72	10.33	0.10563	0.00214



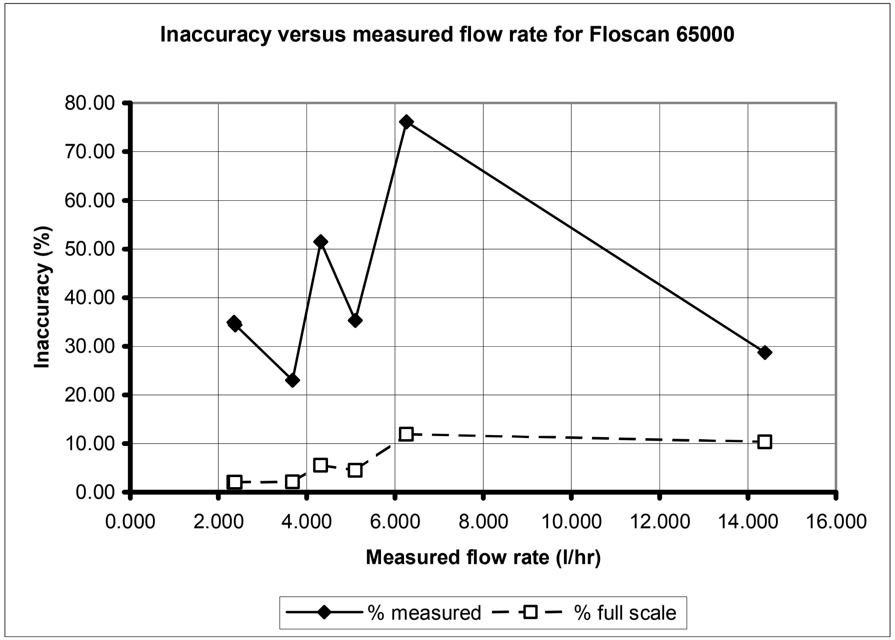


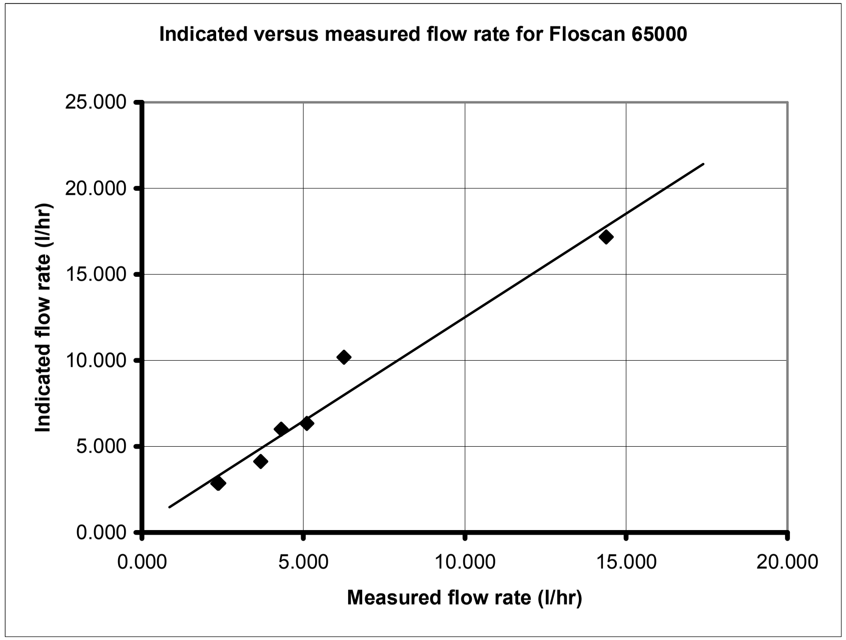
Table 22: "Out-of-the-box" performance of the Floscan Cruisemaster 65000 fuel flow meter, repetition 2

Recalibrated

Engine Flow Summary 2

Floscan 65000

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l	Inaccuracy in Indicated Flow Rate % measured	Inaccuracy in Indicated Flow Rate % full scale	Inaccuracy in Indicated Cumulative Volume % measured	Inaccuracy in Indicated Cumulative Volume % full scale	Variance of Indicated Flow $(l/hr)^2$	Variance of Measured Flow $(l/hr)^2$
Idle	2.0	2.354	2.864	0.144	0.044	21.67	1.28	-69.58	-4.10	0.021	0.00039
Idle	2.0	2.376	2.879	0.145	0.044	21.18	1.26	-69.71	-4.14	0.019	0.00083
Gentle Cruise	2.5	3.680	4.122	0.225	0.063	12.01	1.10	-72.00	-6.62	0.019	0.00010
Cruise & Shoot	3.8	4.320	6.004	0.264	0.092	38.96	4.21	-65.26	-7.05	0.023	0.00022
Haul	4.6	5.104	6.342	0.312	0.097	24.26	3.10	-68.93	-8.80	0.012	0.00041
Steam	5.9	6.262	10.184	0.383	0.156	62.63	9.80	-59.34	-9.29	0.041	0.00686
Trawl	13.9	14.387	17.170	0.879	0.262	19.35	6.96	-70.16	-25.24	0.092	0.00214



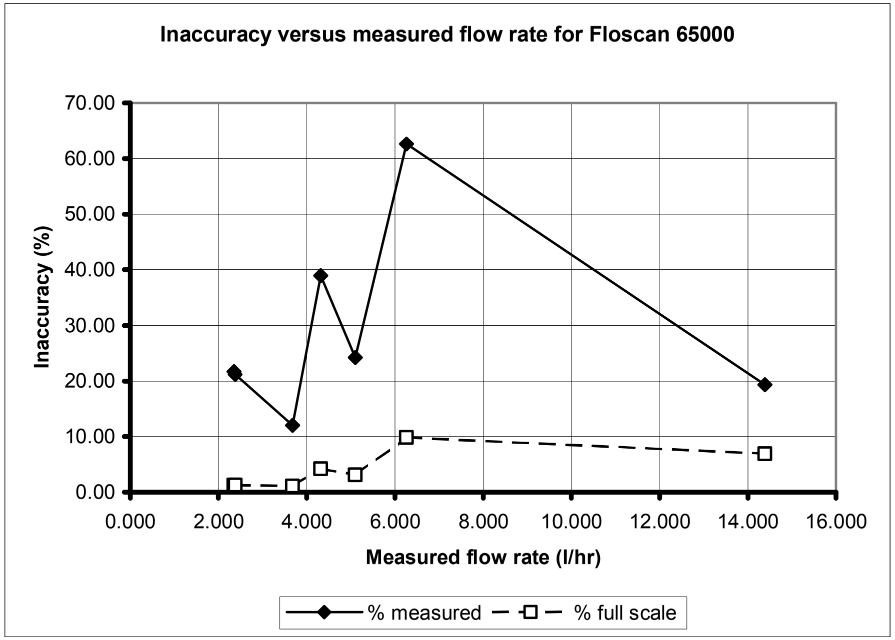


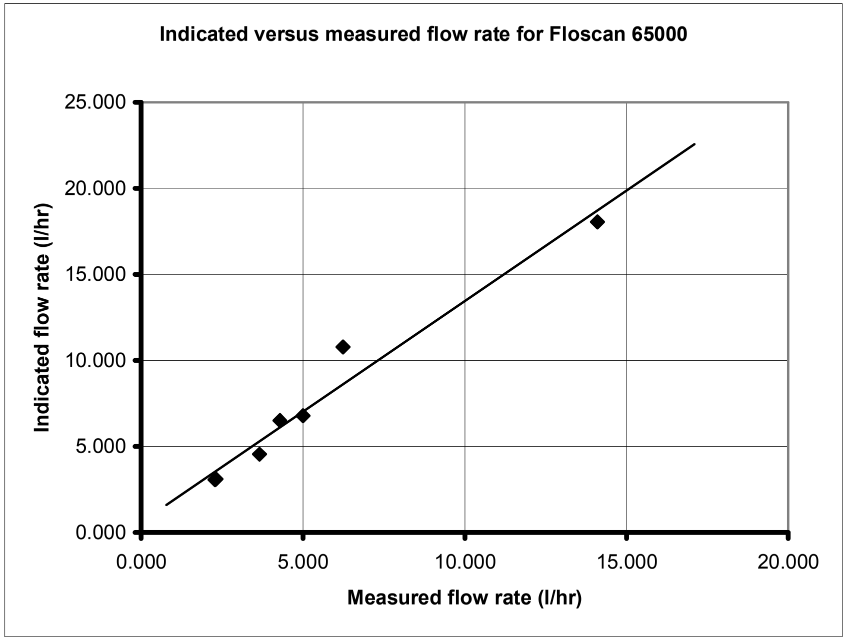
Table 23: "Recalibrated" performance of the Floscan Cruisemaster 65000 fuel flow meter, repetition 2

Engine Flow Summary 3

Floscan 65000

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l
Idle	2.0	2.278	3.072	0.139	0.188
Idle	2.0	2.319	3.097	0.142	0.189
Gentle Cruise	2.5	3.661	4.548	0.224	0.278
Cruise & Shoot	3.8	4.280	6.507	0.262	0.398
Haul	4.6	4.996	6.796	0.305	0.416
Steam	5.9	6.231	10.772	0.381	0.658
Trawl	13.9	14.102	18.045	0.862	1.104

Inaccuracy in Indicated Flow Rate		Inaccuracy in Indicated Cumulative Volume		Variance of Indicated Flow	Variance of Measured Flow
% measured	% full scale	% measured	% full scale	$(l/hr)^2$	$(l/hr)^2$
34.87	1.99	35.04	1.99	0.01301	0.00099
33.55	1.95	33.55	1.95	0.01946	0.00036
24.24	2.22	24.24	2.22	0.01946	0.00031
52.02	5.57	52.02	5.57	0.01807	0.00008
36.03	4.50	36.22	4.52	0.00880	0.00130
72.89	11.35	72.90	11.35	0.02152	0.00443
27.96	9.86	28.14	9.91	0.15183	0.00024



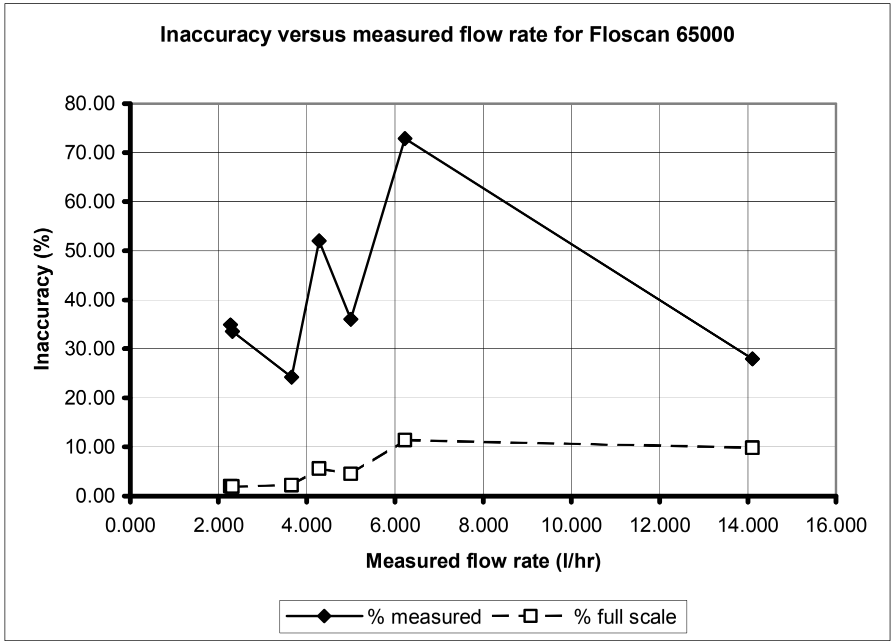


Table 24: "Out-of-the-box" performance of the Floscan Cruisemaster 65000 fuel flow meter, repetition 3

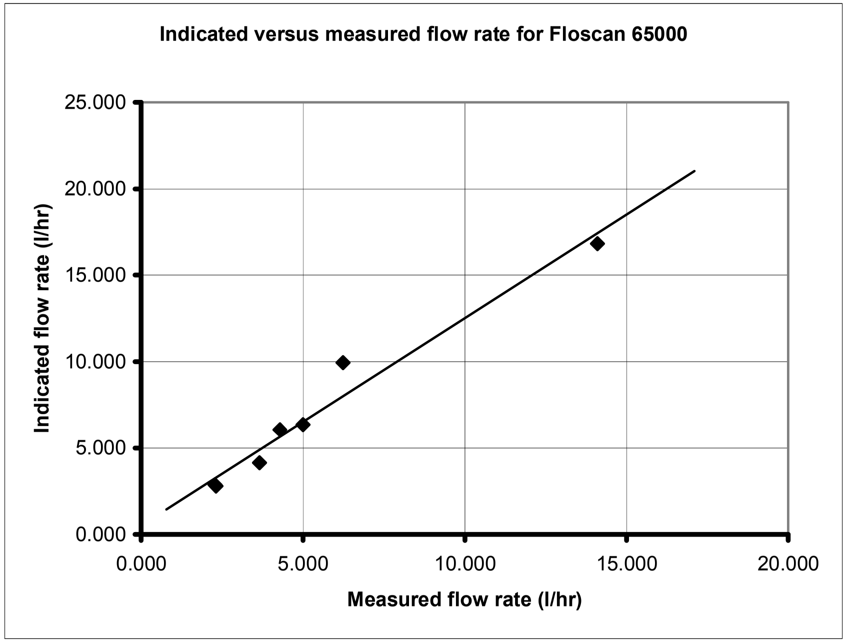
Recalibrated

Engine Flow Summary 3

Floscan 65000

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l
Idle	2.0	2.278	2.864	0.139	0.044
Idle	2.0	2.319	2.790	0.142	0.043
Gentle Cruise	2.5	3.661	4.142	0.224	0.063
Cruise & Shoot	3.8	4.280	6.067	0.262	0.093
Haul	4.6	4.996	6.337	0.305	0.097
Steam	5.9	6.231	9.946	0.381	0.152
Trawl	13.9	14.102	16.825	0.862	0.257

Inaccuracy in Indicated Flow Rate		Inaccuracy in Indicated Cumulative Volume		Variance of Indicated Flow	Variance of Measured Flow
% measured	% full scale	% measured	% full scale	$(l/hr)^2$	$(l/hr)^2$
25.75	1.47	-68.56	-3.90	0.01131	0.00099
20.28	1.18	-69.93	-4.05	0.01692	0.00036
13.16	1.20	-71.71	-6.56	0.01692	0.00031
41.74	4.47	-64.56	-6.91	0.01571	0.00008
26.83	3.35	-68.29	-8.52	0.00765	0.00130
59.62	9.29	-60.10	-9.36	0.01871	0.00443
19.31	6.81	-70.17	-24.71	0.13200	0.00024



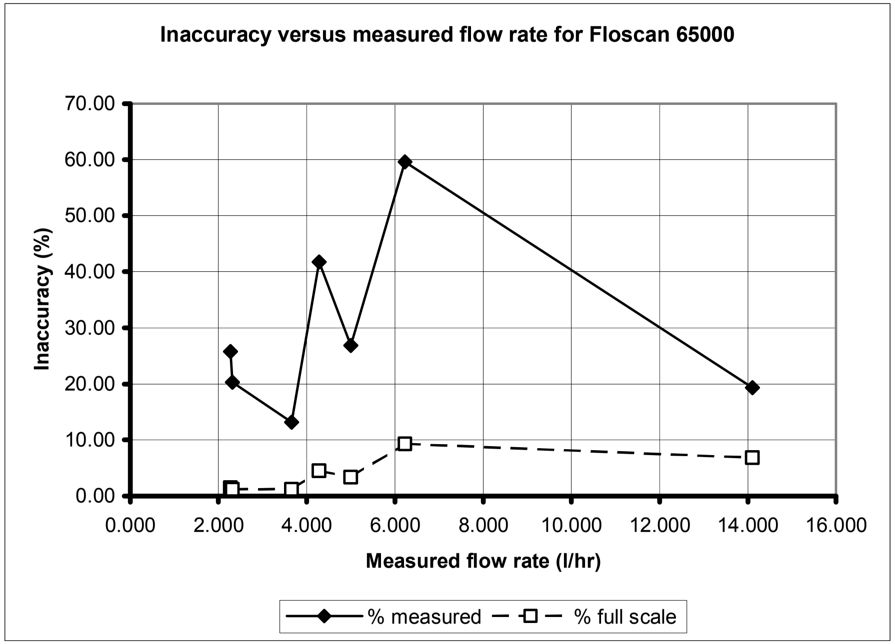


Table 25: "Recalibrated" performance of the Floscan Cruisemaster 65000 fuel flow meter, repetition 3

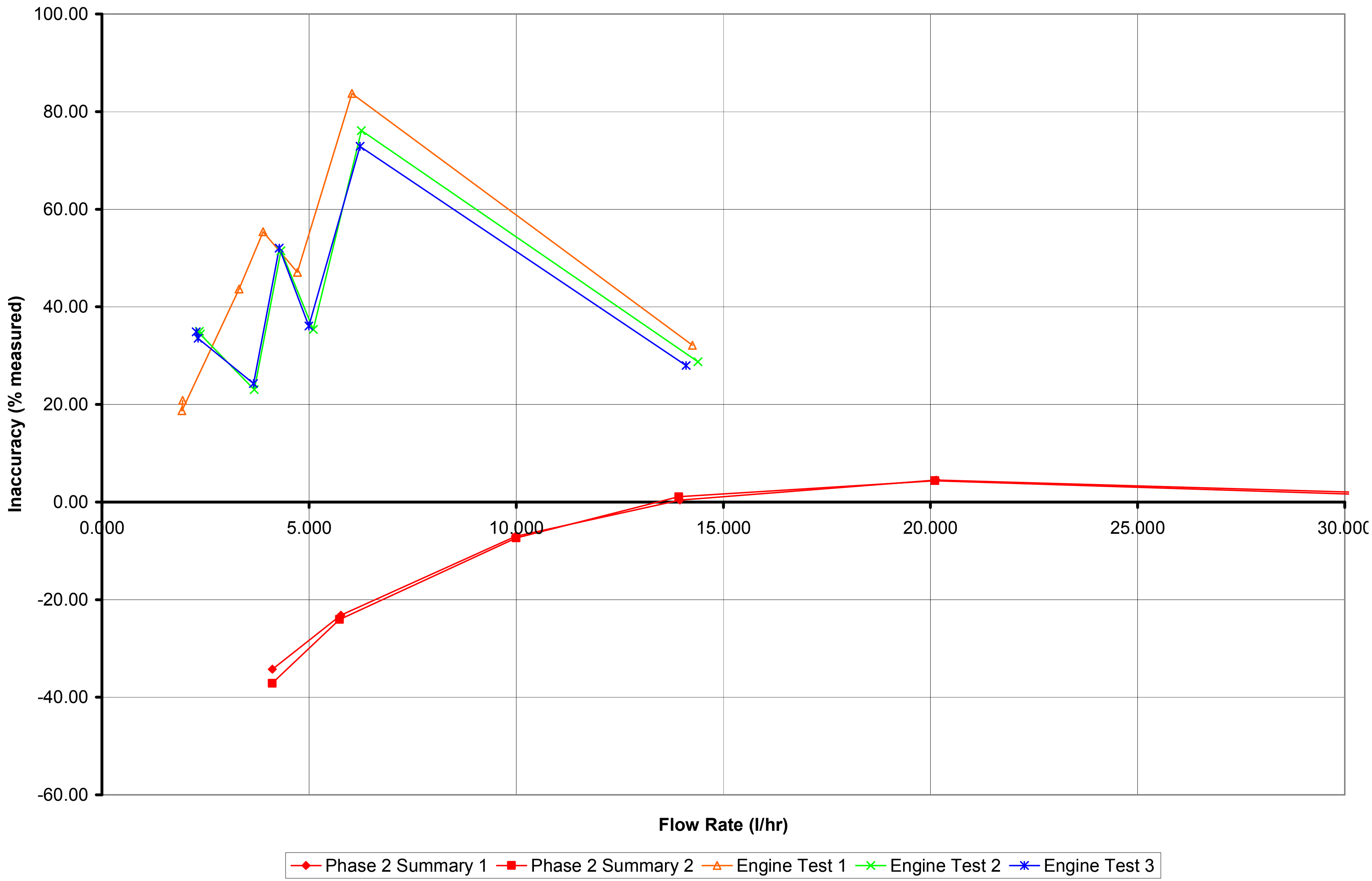


Figure 18: Accuracy versus flowrate for Floscan Cruisemaster 65000 fuel flow meter – "out-of-the-box"

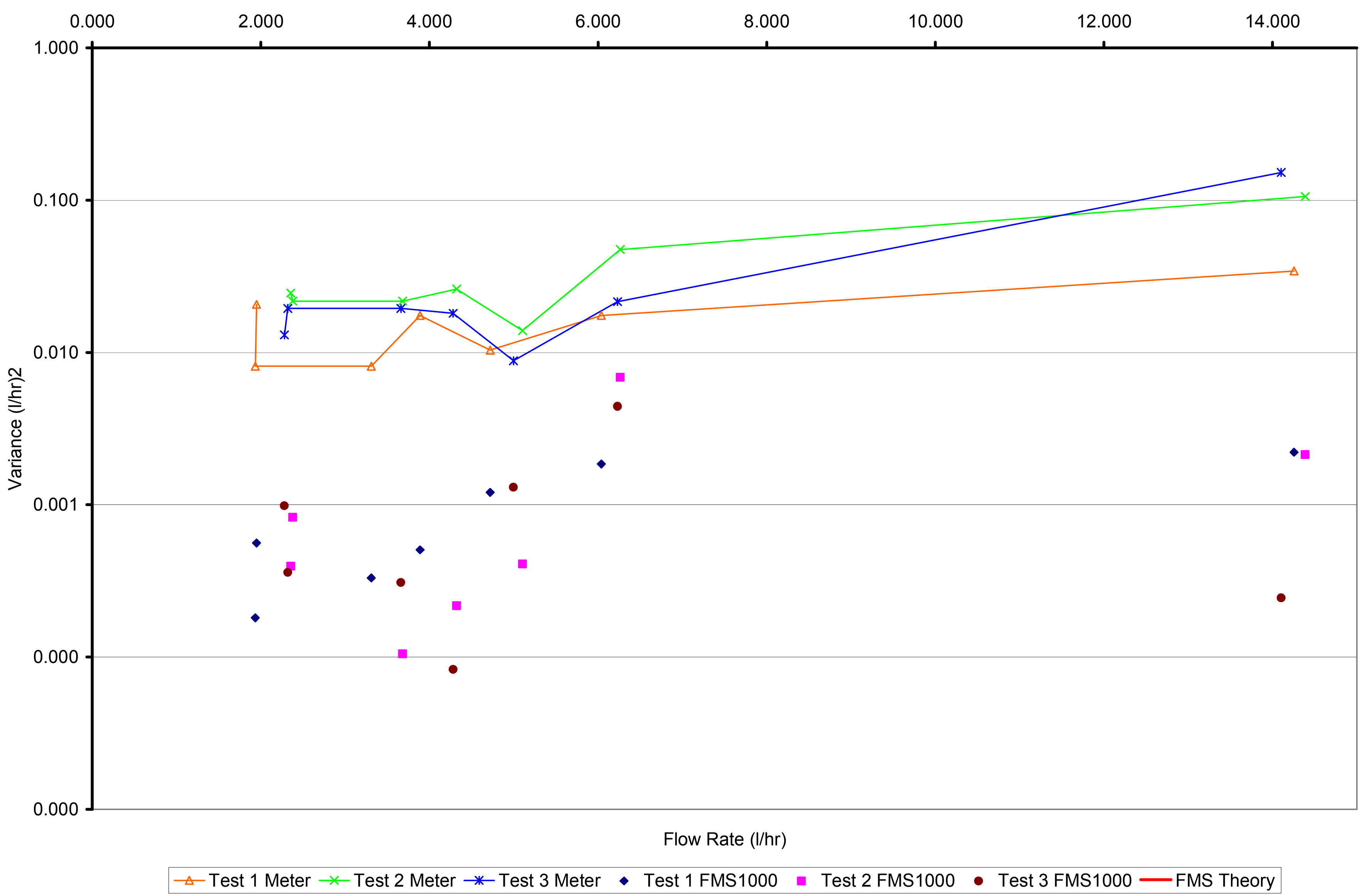


Figure 19: Variance versus flowrate for Floscan Cruisemaster 65000 fuel flow meter – "out-of-the-box"

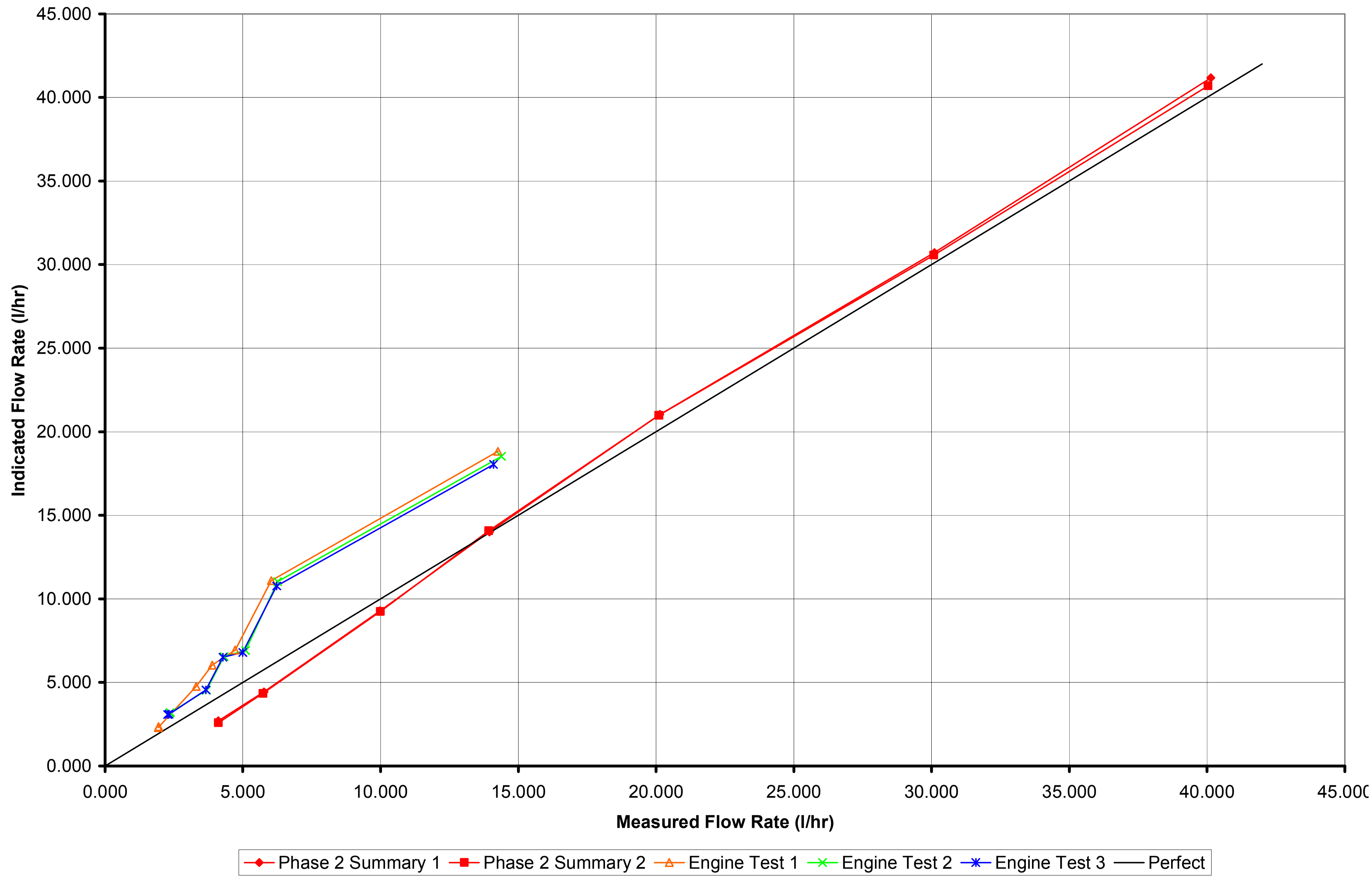


Figure 20: Indicated versus measured flowrate for Floscan Cruisemaster 65000 fuel flow meter – "out-of-the-box"

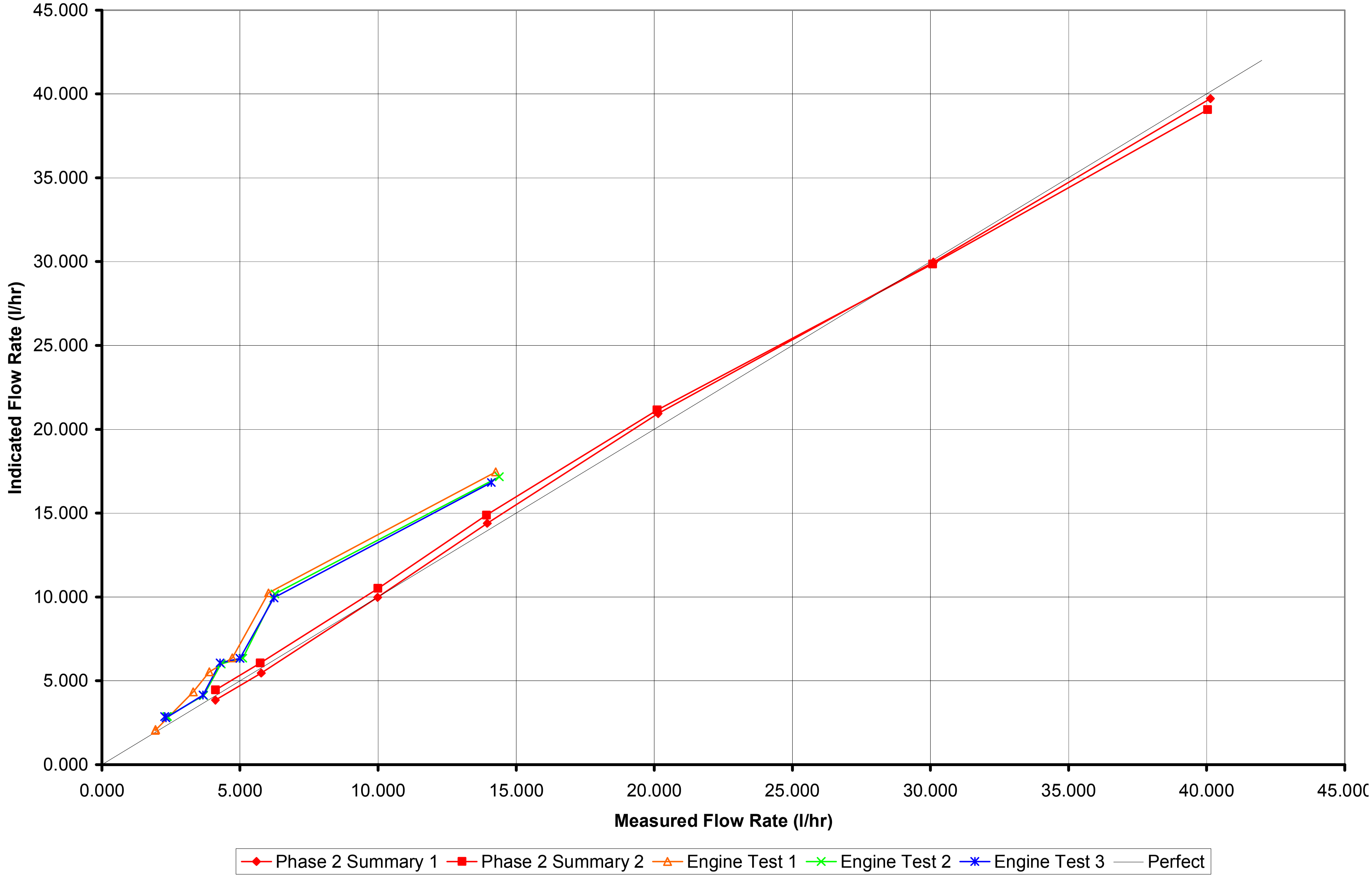


Figure 21: Indicated versus measured flowrate for Floscan Cruisemaster 65000 fuel flow meter – after Phase II calibration

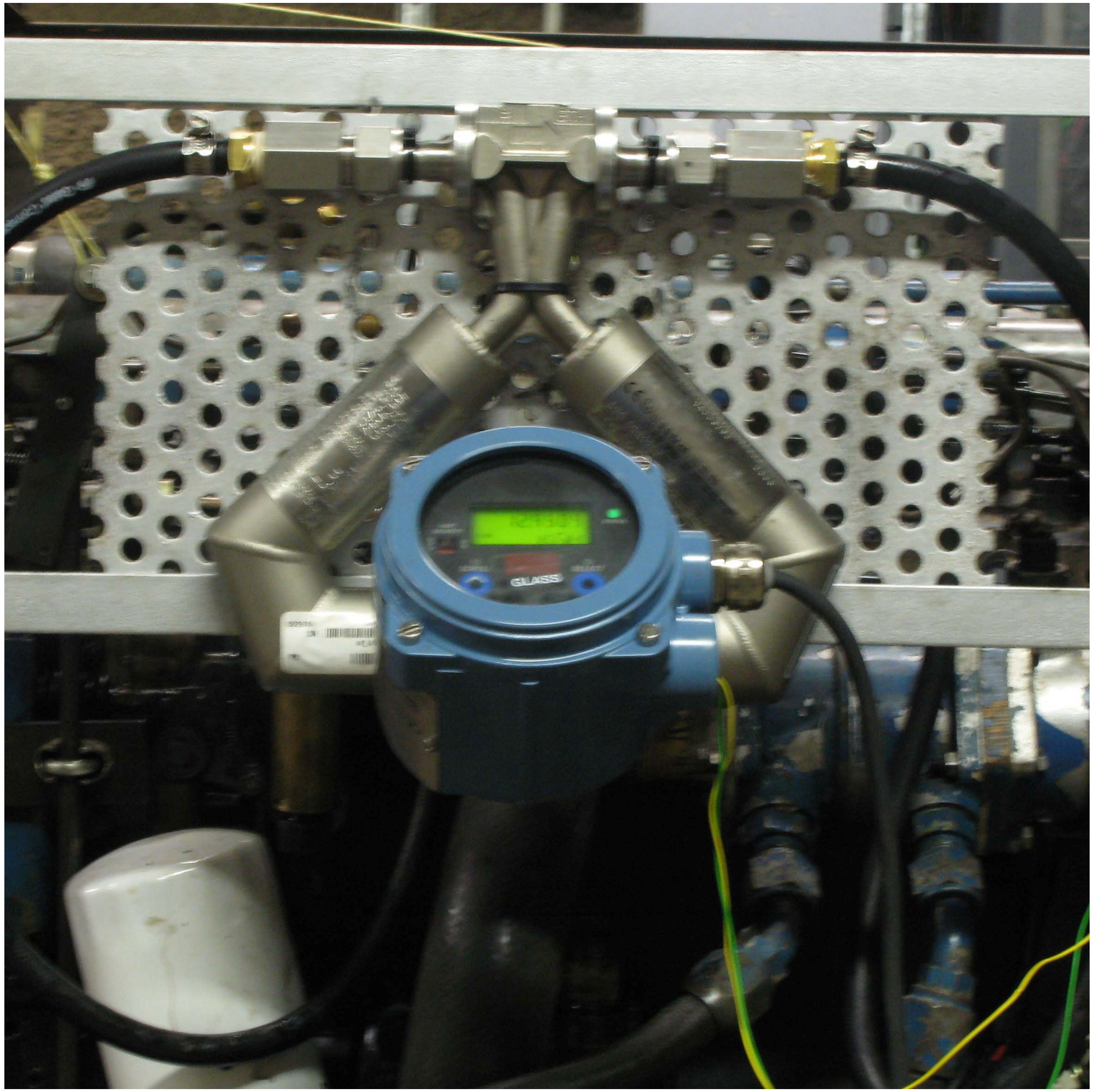
Discussion

There are considerable problems with this meter when put onto an engine. The errors produced are reproducible, but the nonlinearity of the output is such that no reasonable fit could be estimated. Most importantly, the response is very markedly different from Phase II – the pulse dampener is probably not doing its job, as the transducer consistently over-reads.

These results suggest that this transducer is affected so badly by engine flow conditions, it should not be used in a fuel flow monitoring situation. Interestingly, the precision of the device increased relative to Phase II, but this is more than compensated for by the loss in accuracy from an already not-particularly-accurate system.

It should be noted that in testing this fuel metering sensor, the manufacturer's supplied data processing / display unit was not used. Rather, the analogue signal of the device as relayed to the Data Track 284 as was the case for the other devices. It is possible that the manufacturer's data processing / display unit has 'on-board' corrections for some of the non-linearity and inaccuracy that is evident in the results presented.

Emerson CMF025M Micromotion Elite Results

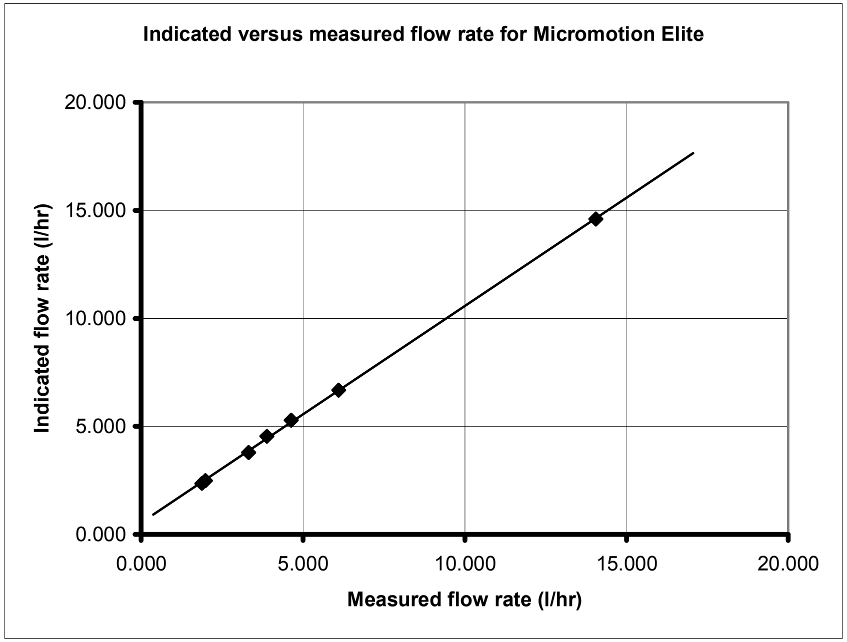


Engine Flow Summary 1

EMERSON MICROMOTION ELITE

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l
Idle	2.0	1.879	2.359	0.115	0.036
Idle	2.0	1.988	2.483	0.121	0.038
Gentle Cruise	2.5	3.320	3.795	0.203	0.058
Cruise & Shoot	3.8	3.880	4.538	0.237	0.069
Haul	4.6	4.629	5.282	0.283	0.081
Steam	5.9	6.101	6.674	0.373	0.102
Trawl	13.9	14.058	14.601	0.859	0.223

Inaccuracy in Indicated Flow Rate		Inaccuracy in Indicated Cumulative Volume		Variance of Indicated Flow	Variance of Measured Flow
% measured	% full scale	% measured	% full scale	$(l/hr)^2$	$(l/hr)^2$
25.58	1.20	-68.61	-3.22	0.0015	0.0017
24.91	1.24	-68.77	-3.42	0.0045	0.0030
14.30	1.19	-71.42	-5.93	0.0045	0.0047
16.95	1.64	-70.76	-6.86	0.1318	0.0026
14.11	1.63	-71.47	-8.27	0.0196	0.0013
9.41	1.43	-72.65	-11.08	0.0033	0.0029
3.86	1.36	-74.03	-26.02	0.0068	0.0038



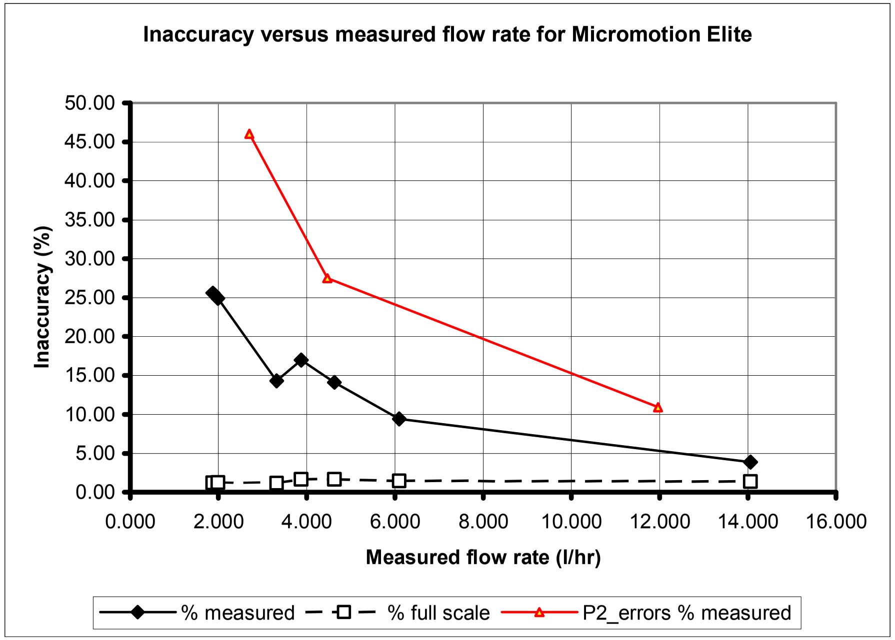


Table 26: "Out-of-the-box" performance of the Emerson CMF025M Micromotion Elite fuel flow meter, repetition 1

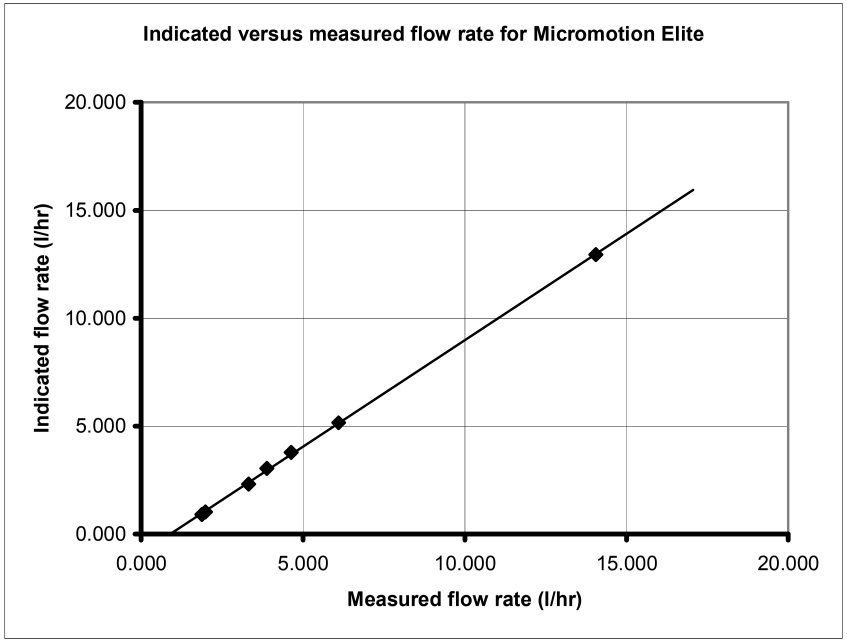
Recalibrated

Engine Flow Summary 1

EMERSON MICROMOTION ELITE

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l
Idle	2.0	1.879	0.911	0.115	0.056
Idle	2.0	1.988	1.032	0.121	0.063
Gentle Cruise	2.5	3.320	2.322	0.203	0.142
Cruise & Shoot	3.8	3.880	3.052	0.237	0.187
Haul	4.6	4.629	3.784	0.283	0.231
Steam	5.9	6.101	5.152	0.373	0.315
Trawl	13.9	14.058	12.942	0.859	0.791

Inaccuracy in Indicated Flow Rate		Inaccuracy in Indicated Cumulative Volume		Variance of Indicated Flow	Variance of Measured Flow
% measured	% full scale	% measured	% full scale	$(l/hr)^2$	$(l/hr)^2$
-51.51	-2.42	-51.51	-2.42	0.0014	0.0017
-48.08	-2.39	-48.08	-2.39	0.0044	0.0030
-30.07	-2.50	-30.08	-2.50	0.0044	0.0047
-18.26	-2.11	-18.27	-2.11	0.1273	0.0026
-18.26	-2.11	-18.27	-2.11	0.0189	0.0013
-15.56	-2.37	-15.56	-2.37	0.0032	0.0029
-7.94	-2.79	-7.94	-2.79	0.0066	0.0038



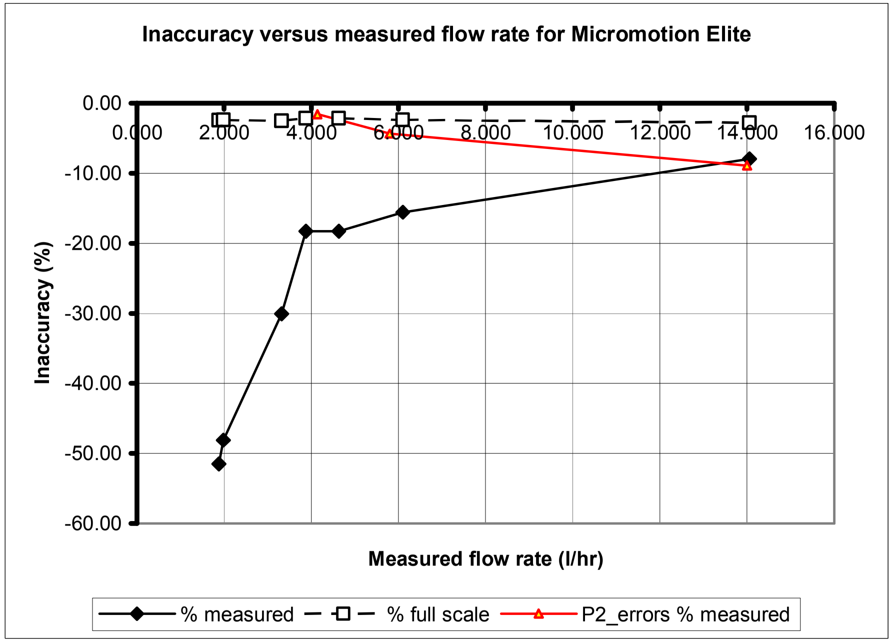
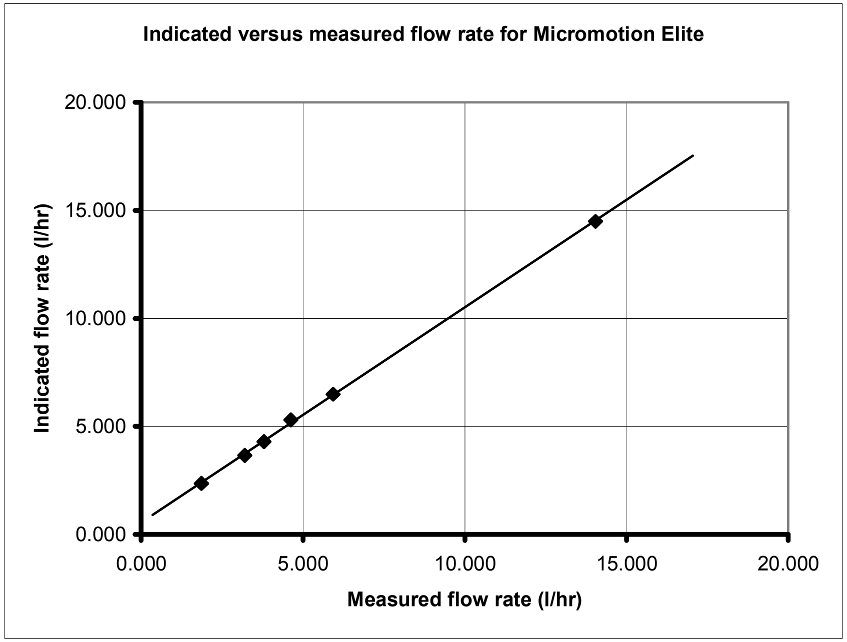


Table 27: "Recalibrated" performance of the CMF025M Micromotion Elite fuel flow meter, repetition 1

Engine Flow Summary 2

EMERSON MICROMOTION ELITE

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l	Inaccuracy in Indicated Flow Rate % measured	Inaccuracy in Indicated Flow Rate % full scale	Inaccuracy in Indicated Cumulative Volume % measured	Inaccuracy in Indicated Cumulative Volume % full scale	Variance of Indicated Flow $(l/hr)^2$	Variance of Measured Flow $(l/hr)^2$
Idle	2.0	1.870	2.357	0.114	0.036	26.03	1.22	-68.49	-3.20	0.0002	0.0005
Idle	2.0	1.860	2.358	0.114	0.036	26.79	1.25	-68.30	-3.18	0.0002	0.0003
Gentle Cruise	2.5	3.195	3.655	0.195	0.056	14.39	1.15	-71.40	-5.70	0.0002	0.0001
Cruise & Shoot	3.8	3.798	4.304	0.232	0.066	13.34	1.27	-71.67	-6.80	0.1462	0.0001
Haul	4.6	4.621	5.297	0.282	0.081	14.64	1.69	-71.34	-8.24	0.0004	0.0011
Steam	5.9	5.938	6.498	0.363	0.099	9.43	1.40	-72.64	-10.78	0.0007	0.0011
Trawl	13.9	14.050	14.493	0.859	0.221	3.15	1.11	-74.21	-26.13	0.0059	0.0037



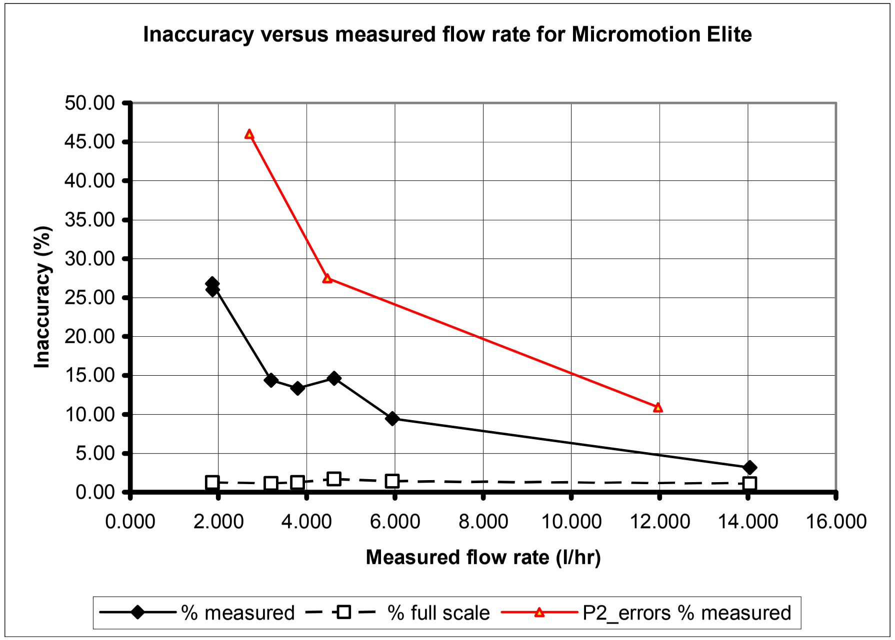


Table 28: "Out-of-the-box" performance of the CMF025M Micromotion Elite fuel flow meter, repetition 2

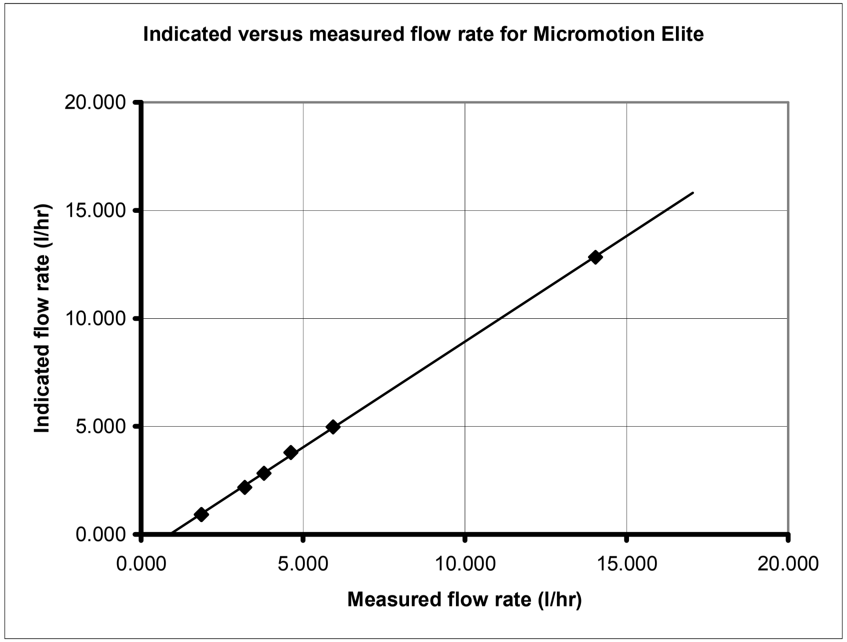
Recalibrated

Engine Flow Summary 2

EMERSON MICROMOTION ELITE

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l
Idle	2.0	1.870	0.909	0.114	0.056
Idle	2.0	1.860	0.910	0.114	0.056
Gentle Cruise	2.5	3.195	2.184	0.195	0.133
Cruise & Shoot	3.8	3.798	2.823	0.232	0.172
Haul	4.6	4.621	3.798	0.282	0.232
Steam	5.9	5.938	4.978	0.363	0.304
Trawl	13.9	14.050	12.836	0.859	0.783

Inaccuracy in Indicated Flow Rate		Inaccuracy in Indicated Cumulative Volume		Variance of Indicated Flow	Variance of Measured Flow
% measured	% full scale	% measured	% full scale	$(l/hr)^2$	$(l/hr)^2$
-51.40	-2.40	-51.40	-2.40	0.00016	0.00054
-51.08	-2.38	-51.08	-2.38	0.00020	0.00026
-31.64	-2.53	-31.64	-2.53	0.00020	0.00008
-25.68	-2.44	-25.68	-2.44	0.14121	0.00007
-17.79	-2.06	-17.79	-2.06	0.00038	0.00113
-16.16	-2.40	-16.16	-2.40	0.00064	0.00106
-8.64	-3.04	-8.85	-3.12	0.00568	0.00366



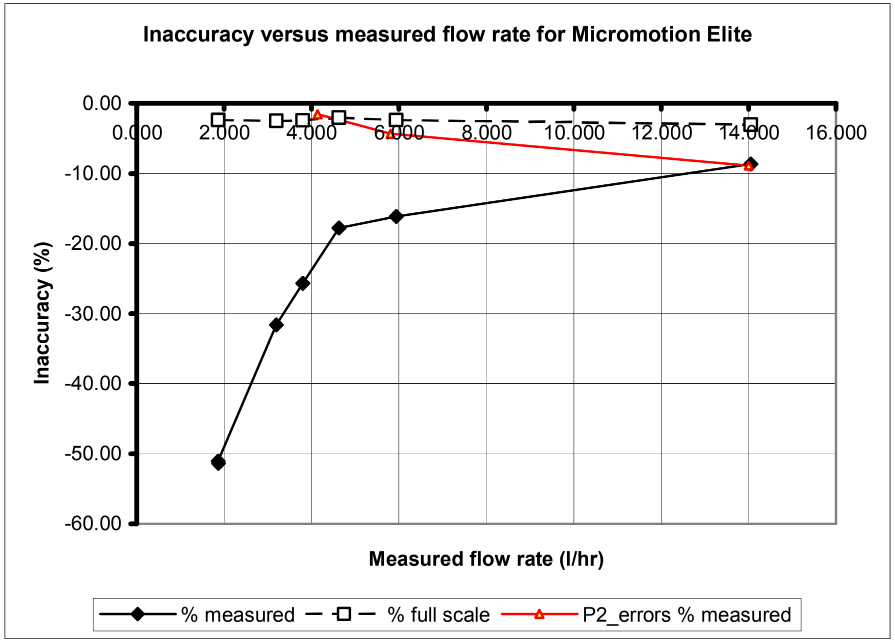


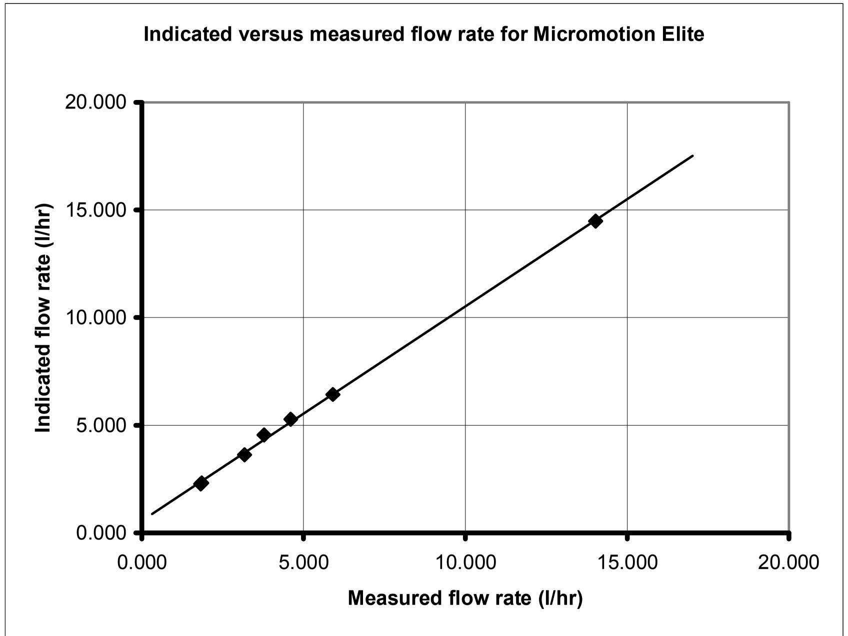
Table 29: "Recalibrated" performance of the CMF025M Micromotion Elite fuel flow meter, repetition 2

Engine Flow Summary 3

EMERSON MICROMOTION ELITE

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l
Idle	2.0	1.816	2.270	0.111	0.035
Idle	2.0	1.851	2.325	0.113	0.036
Gentle Cruise	2.5	3.174	3.624	0.194	0.055
Cruise & Shoot	3.8	3.777	4.558	0.231	0.070
Haul	4.6	4.604	5.278	0.281	0.081
Steam	5.9	5.908	6.430	0.361	0.098
Trawl	13.9	14.027	14.487	0.857	0.221

Inaccuracy in Indicated Flow Rate		Inaccuracy in Indicated Cumulative Volume		Variance of Indicated Flow $(l/hr)^2$	Variance of Measured Flow $(l/hr)^2$
% measured	% full scale	% measured	% full scale		
24.99	1.13	-68.75	-3.12	0.0003	0.0011
25.58	1.18	-68.60	-3.18	0.0002	0.0004
14.18	1.13	-71.46	-5.67	0.0002	0.0001
20.67	1.95	-69.83	-6.59	0.8466	0.0001
14.63	1.68	-71.34	-8.21	0.0013	0.0010
8.83	1.30	-72.79	-10.75	0.0012	0.0010
3.28	1.15	-74.18	-26.01	0.0057	0.0017



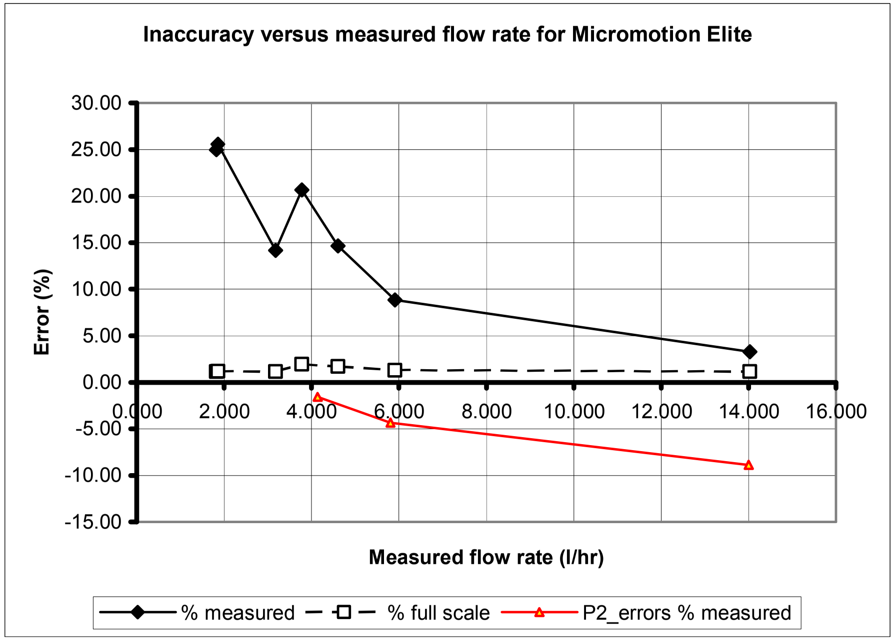


Table 30: "Out-of-the-box" performance of the CMF025M Micromotion Elite fuel flow meter, repetition 3

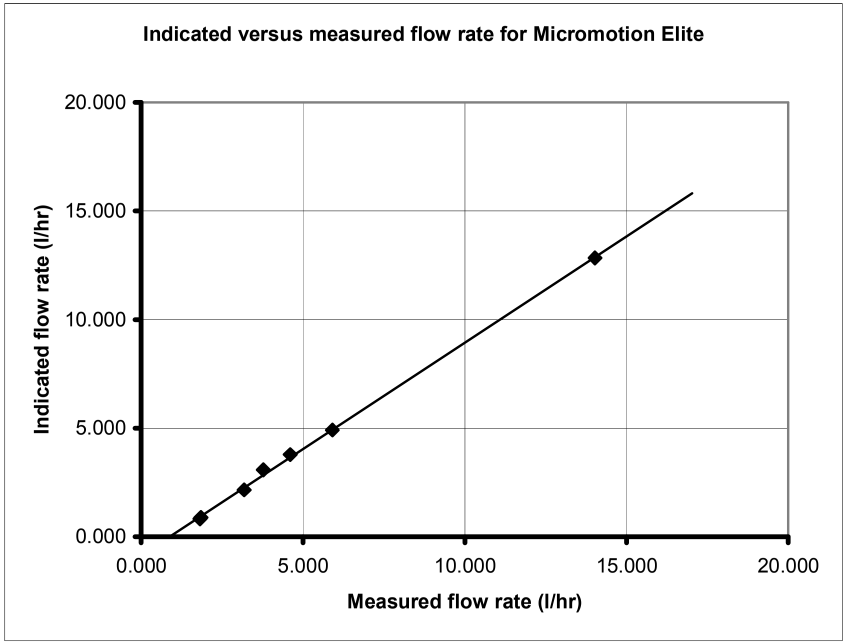
Recalibrated

Engine Flow Summary 3

EMERSON MICROMOTION ELITE

Test Point	Estimated Flow rate l/hr	FMS measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	FMS Cumulative Volume l	Meter Indicated Cumulative Volume l
Idle	2.0	1.816	0.823	0.111	0.050
Idle	2.0	1.851	0.877	0.113	0.054
Gentle Cruise	2.5	3.174	2.154	0.194	0.132
Cruise & Shoot	3.8	3.777	3.072	0.231	0.188
Haul	4.6	4.604	3.779	0.281	0.231
Steam	5.9	5.908	4.911	0.361	0.300
Trawl	13.9	14.027	12.830	0.857	0.784

Inaccuracy in Indicated Flow Rate		Inaccuracy in Indicated Cumulative Volume		Variance of Indicated Flow $(l/hr)^2$	Variance of Measured Flow $(l/hr)^2$
% measured	% full scale	% measured	% full scale		
-54.67	-2.48	-54.67	-2.48	0.0003	0.0011
-52.62	-2.44	-52.62	-2.44	0.0002	0.0004
-32.14	-2.55	-32.14	-2.55	0.0002	0.0001
-18.67	-1.76	-18.72	-1.77	0.8176	0.0001
-17.92	-2.06	-17.92	-2.06	0.0012	0.0010
-16.87	-2.49	-16.87	-2.49	0.0011	0.0010
-8.53	-2.99	-8.53	-2.99	0.0055	0.0017



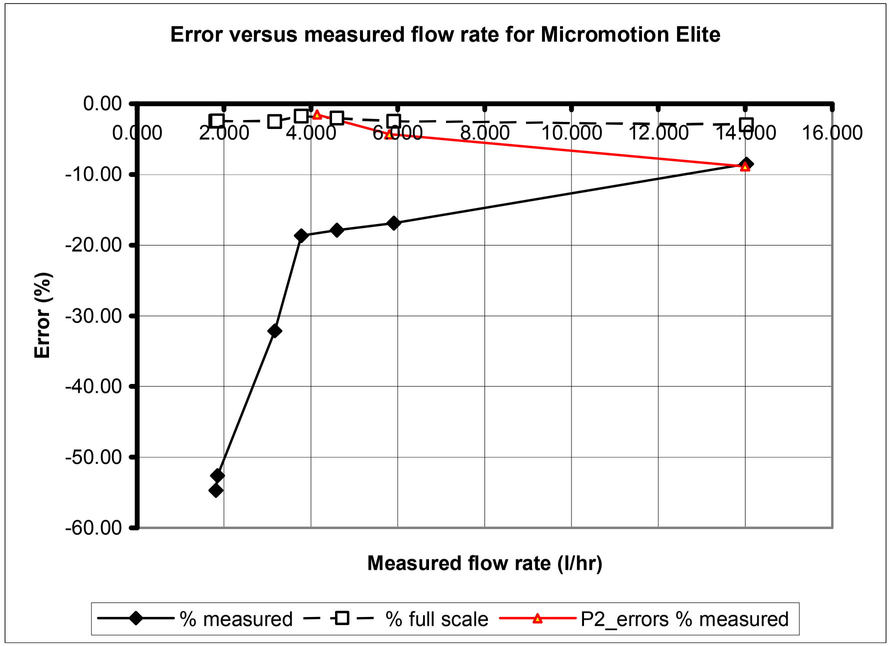


Table 31: "Recalibrated" performance of the CMF025M Micromotion Elite fuel flow meter, repetition 3

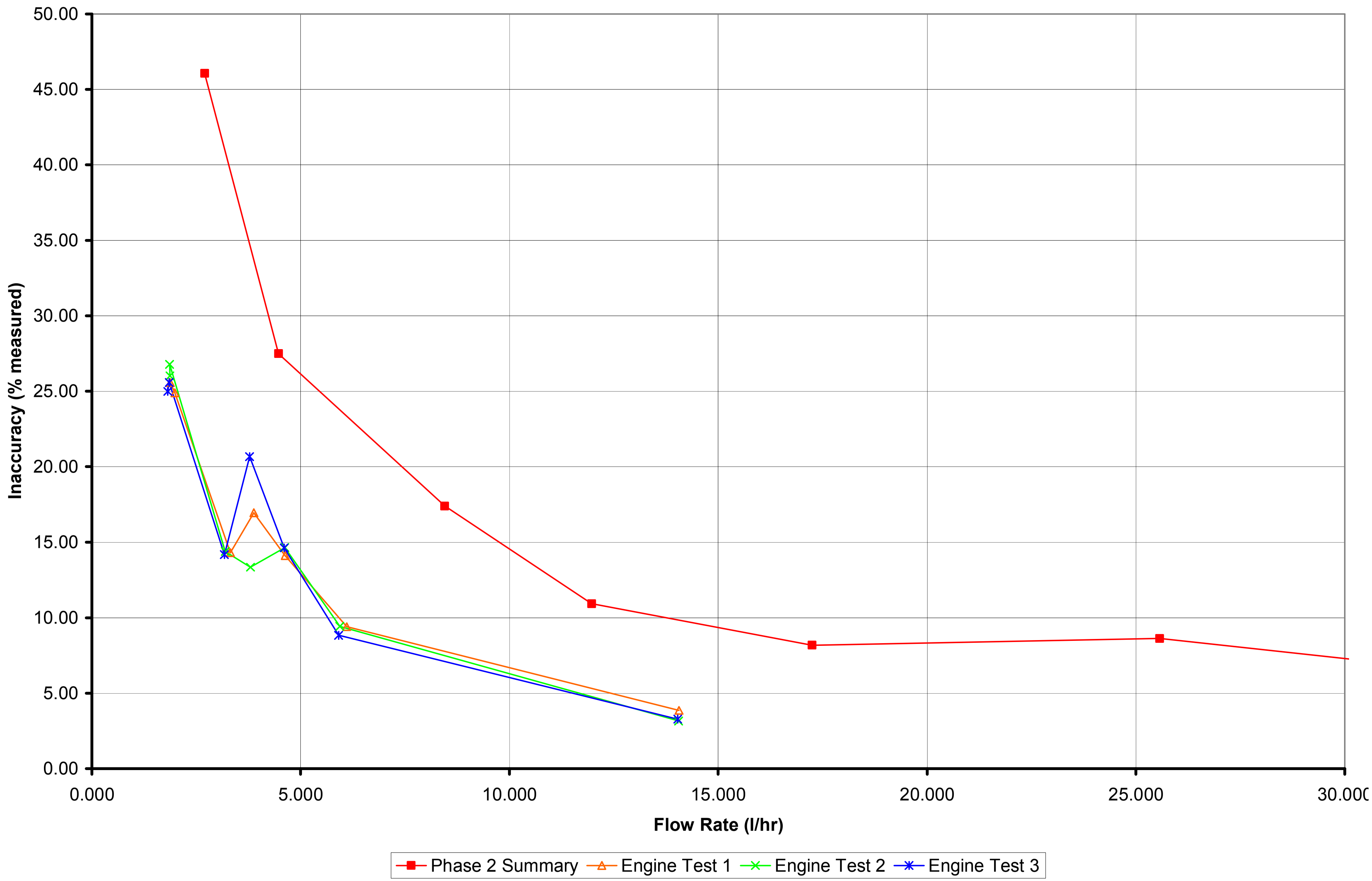


Figure 22: Accuracy versus flowrate for CMF025M Micromotion Elite fuel flow meter – "out-of-the-box"

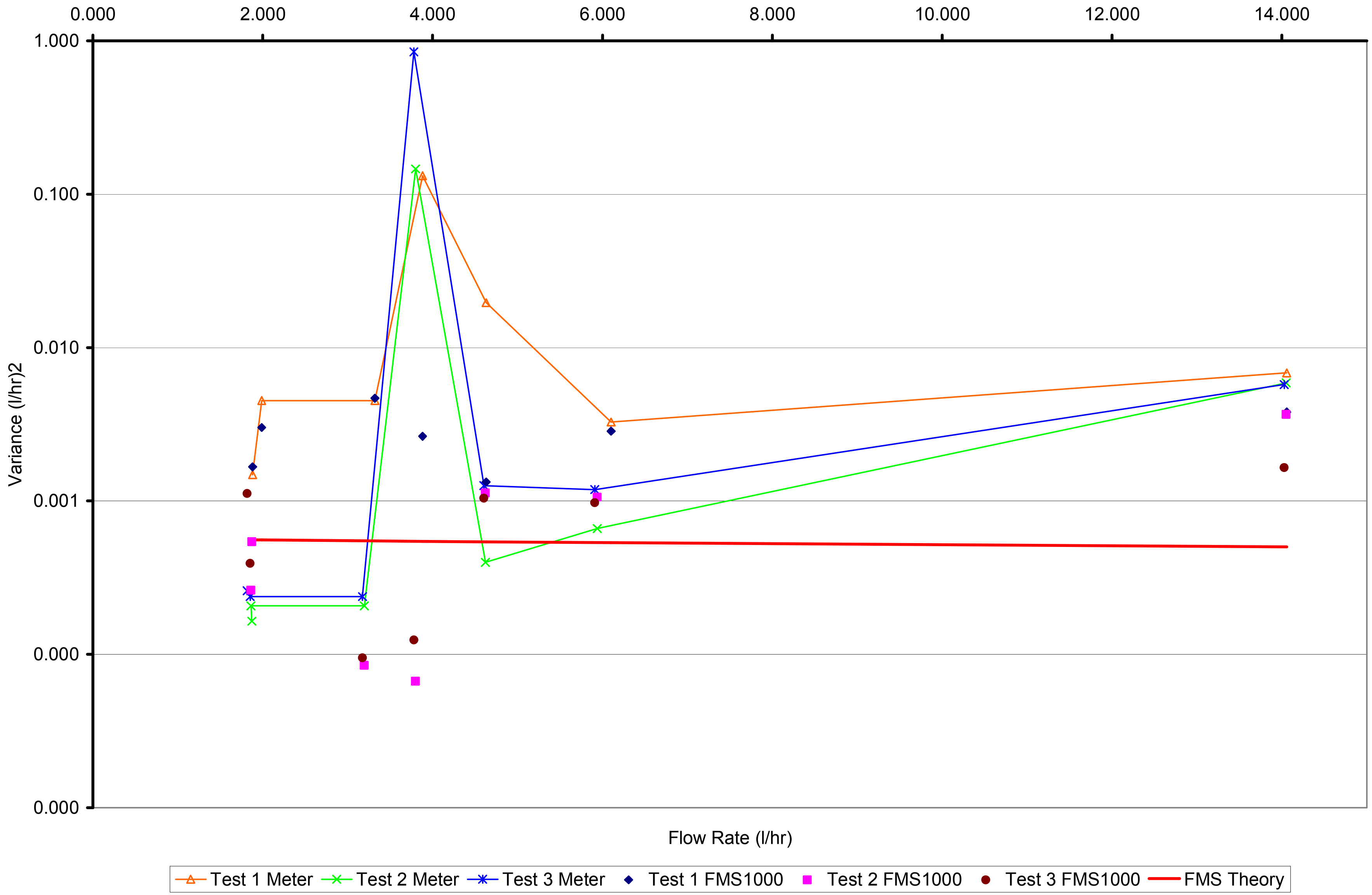


Figure 23: Variance versus flowrate for CMF025M Micromotion Elite fuel flow meter – "out-of-the-box"

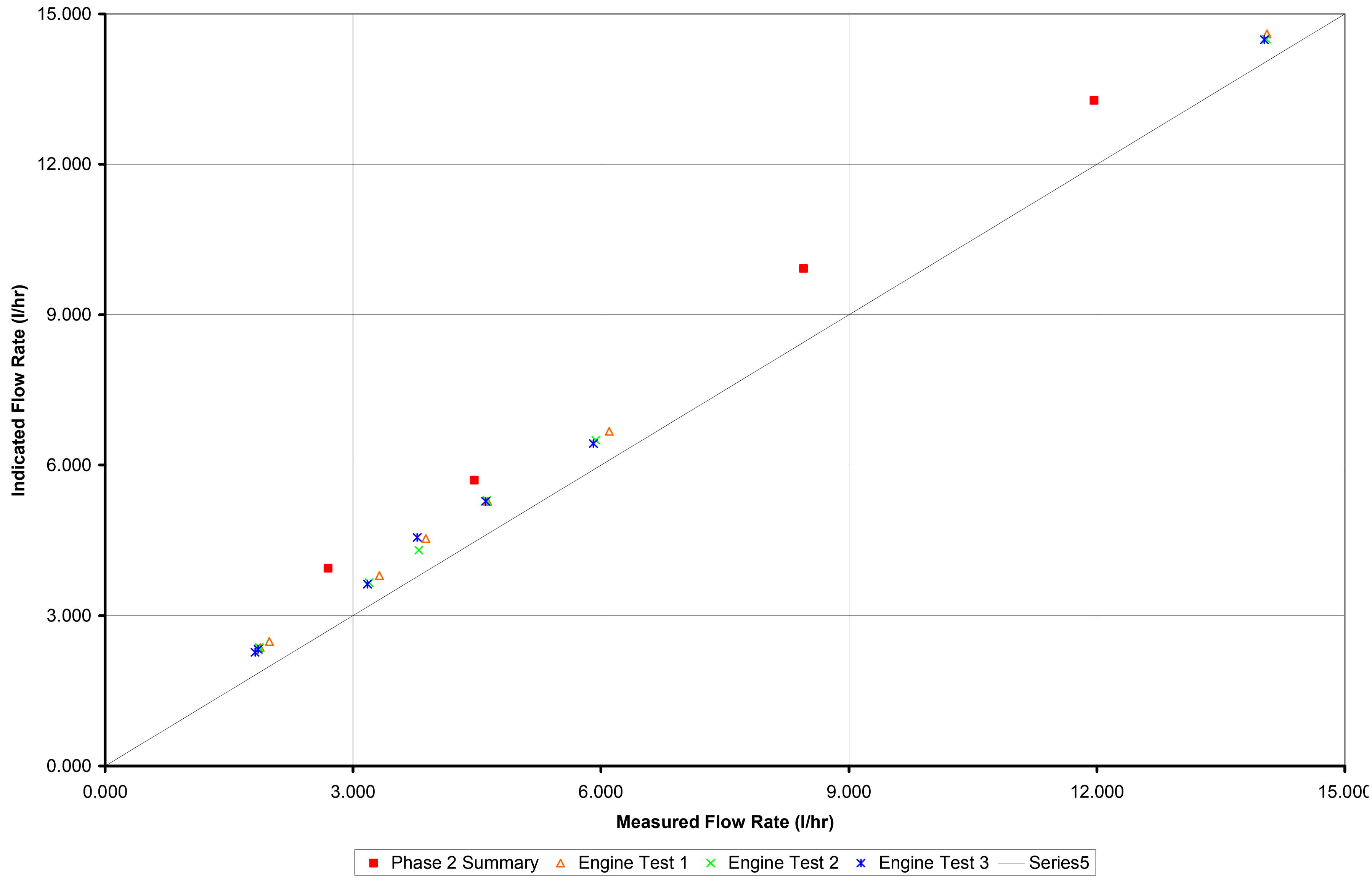


Figure 24: Indicated versus measured flowrate for CMF025M Micromotion Elite fuel flow meter – "out-of-the-box"

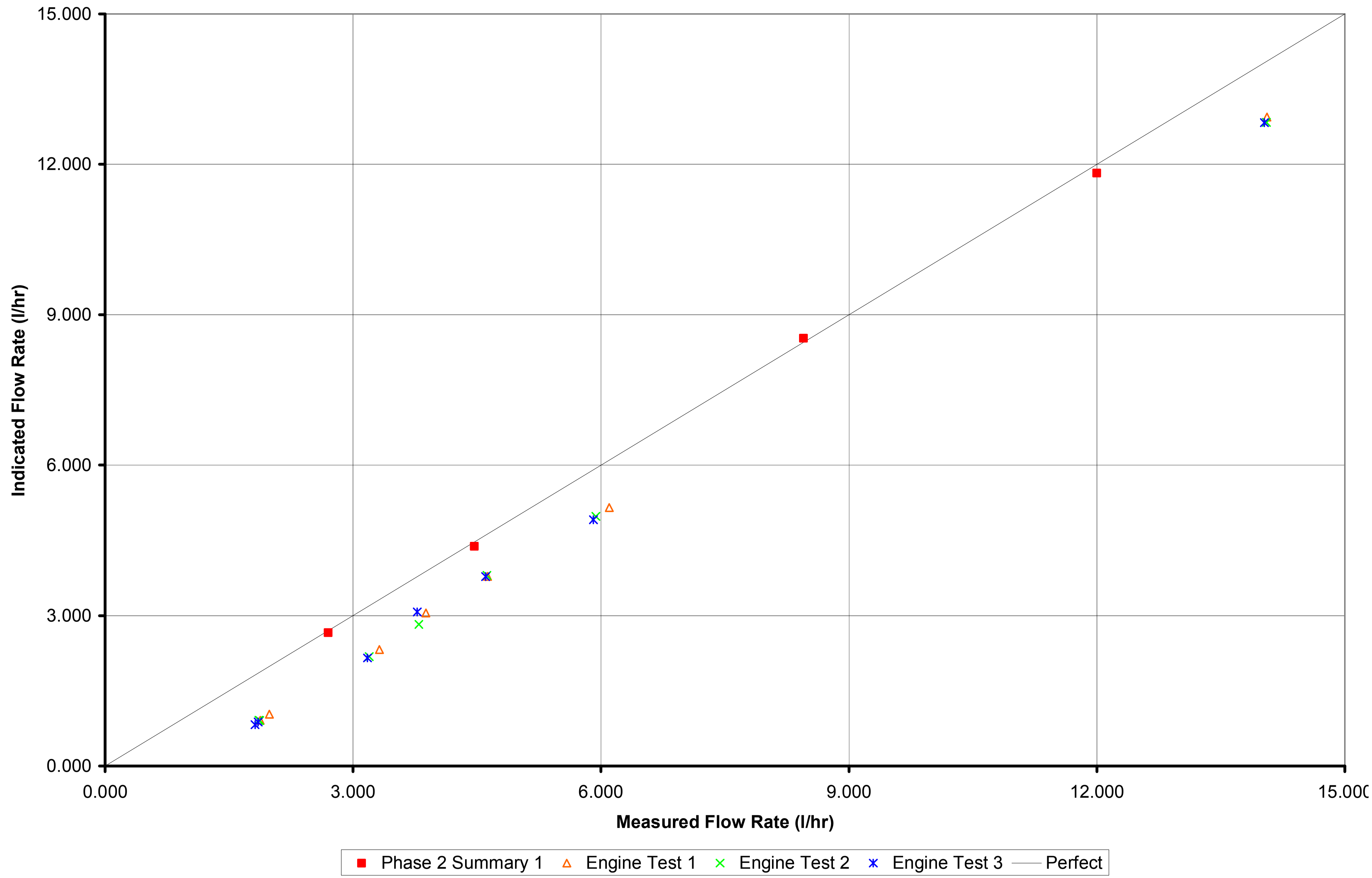


Figure 25: Indicated versus measured flowrate for CMF025M Micromotion Elite fuel flow meter – after Phase II calibration

Discussion

It is interesting that this device actually seems to have become more accurate on the engine! Also of note is the large variance spike at one test point repeated in all tests. The manufacturer claims that little except putting another coriolis meter operating on the same frequency in line with one of these meters will cause resonance errors, but this sort of spike can signify little else. Obviously, this does not preclude the use of a coriolis meter, but care must be taken that it is set up so that there is no possibility that the engine will produce frequencies close to the operating frequency of the device. The very high precision of the device overall is notable, though a slight nonlinearity of output can be seen, greater than that of the oval gear meters, meaning that even recalibrated, the oval gear meters may still be the more accurate. The large turn-down ratio of this device must then be brought back into mind.

It is suspected that the reason for the relatively poor performance of the Emerson CMF025M is the fact that it is physically rated for a much higher flow rate than any of the other devices, but its instrumentation was set to a turn down ratio of 50 by the supplier, for the purposes of this work. Better performance of this type of flow meter should be expected if a device with a physical rating closer matched to the range of test and engine fuel flow rates is used.

Summary of Results

While the previous sections detailing the results of testing for each of the meters have been necessary for the sake of completeness of reporting, in this section the results of both Phase II (off engine) and Phase III work are summarised in Table 32 in order that the findings of the work can be identified and appreciated by the reader.

Table 32: Summary of flow meter test results from Phase II and Phase III

Device	Test	Oval Flowmate MIII	Macnaught M1	Kobold DRZ	Floscan C/M 65000	Emerson CMF025M Elite
Meter Type		Oval gear	Oval gear	Oscillating piston	Turbine meter	Coriollis meter
Quoted accuracy (%FS, unless specified)		0.50%	0.50%	1.00% (of observation)	Not reported	
FSD flowrate (l/h)		100	100	420	Not reported	2180 [5]kg/h
Cost (£)		£185	£263	£258	£583	£3000-£4000
PHASE II						
Inaccuracy of indicated flowrate "out-of-the-box" (% 4.2 l/h)	1	4.57%	5.58%	-34.09%	-34.20%	46.07%
	2		4.31%		-36.91%	
Inaccuracy of indicated flowrate after calibration (% 4.2 l/h)	1	9.75%	-3.13%	-30.64%	-6.28%	-6.07%
	2		5.60%		8.54%	
Inaccuracy of indicated flowrate "out-of-the-box" (%FS)	1	0.30%	0.40%	2.72%	2.54%	3.93%
	2		0.36%		2.61%	
Inaccuracy of indicated flowrate after calibration (%FS)	1	0.36%	0.30%	1.33%	0.98%	0.67%
	2		0.42%		1.59%	
Observed repeatability (l/h) (Standard deviation @ 25% FS)	1	0.12	0.12	0.54	0.23	0.13
	2		0.17		0.12	
Observed repeatability (l/h) (Standard deviation @ 75% FS)	1	0.30	0.34	1.02 [4]	0.39	0.18
	2		0.55		0.50	
PHASE III						
Inaccuracy of indicated flowrate "out-of-the-box" (% of 4.6 l/h)	1	6.56%	12.62%	-8.25%	47.05%	14.11%
	2	7.16%	7.27%	-13.41%	35.34%	14.64%
	3	6.72%	14.18%	-13.64%	36.03%	16.63%
Inaccuracy of indicated flowrate after calibration (% of 4.6 l/h)	1	6.20%	4.55%	-1.15%	35.02%	-18.26%
	2	6.81%	-0.98%	-6.72%	24.26%	-17.79%
	3	6.36%	5.99%	-6.96%	26.83%	-17.92%
Inaccuracy of indicated flowrate "out-of-the-box" (%FS)	1	0.32%	0.37%	0.12%	7.22%	1.40%
	2	0.33%	0.33%	0.19%	6.69%	1.31%
	3	0.33%	0.70%	0.19%	6.44%	1.40%
Inaccuracy of indicated flowrate after calibration (%FS)	1	0.30%	0.13%	0.03%	5.55%	2.39%
	2	0.31%	0.09%	0.08%	5.02%	2.48%
	3	0.31%	0.37%	0.09%	4.91%	2.42%
Observed repeatability RMS Standard deviation (l/h)	1	0.029	0.123	0.045	0.129	0.082 [2]
	2	0.035	0.052	0.031	0.193	0.035 [2]
	3	0.034	0.345	0.028	0.190	0.039 [2]
Observed repeatability of FMS1000, RMS Standard deviation (l/h)	1	0.029	0.029	0.031	0.031	0.053
	2	0.027	0.042 [3]	0.034	0.040	0.031
	3	0.029	0.040 [3]	0.028	0.033	0.028
Average uncertainty relative to FMS1000	1	0.98	4.29 [1]	1.43	4.13	1.53 [2]
	2	1.32	1.25	0.94	4.88	1.14 [2]
	3	1.17	8.69	0.98	5.72	1.39 [2]

Notes
1. Excluding outlier on Haul stage
2. Excluding outlier on Cruise & Shoot stages
3. Excluding outlier on Trawl stage
4. Highest flowrate obtained with this test was ~66% of rated flow using feed pump
5. Emerson CMF025M physically rated at 2180 kg/h but set, and assessed, with a turn down ratio of 50, e.g. 40 kg/h

For the Kobold DRZ, after the Phase II report was submitted, the voltage output from the Data Track 284 was re-ranged to be more compatible with the full scale flow rate of this device, and the Phase II testing re-done. The results shown in Phase II section of Table 32 are for the repeat tests and have resulted in a revision of the Phase II rank of this device, across all the devices tested.

Explanation of row headings in Summary Results table

The table is divided into 3 sections. The upper section is a header area providing the name of the device, its type, its full scale deflection value (flow rate rating), its manufacturer's quoted accuracy and its cost, as procured by in this project (ex. VAT). The middle section of Table 32 summarises the results from Phase II testing and the lower section summarises the results from Phase III testing.

Phase II section

Inaccuracy of indicated flowrate "out-of-the-box" (% 4.2 l/h)

These figures expresses the accuracy of observations made by the meter under test for the lowest flow rate set point tested in Phase II, nominally 4.2 litres / hour, the most demanding condition tested. Equivalent figures for higher flow rates will be lower, that is they will reflect better accuracy. The term "out-of-the-box" means that these results imply that the flow meter has been procured and fitted to a test rig without any consideration given to calibration of the device *in-situ*. The manufacturers quoted conversion factors to translate the sensed observation (voltage, counts, frequency, current, etc.) to flow rate are trusted. Data from up to two repeat tests are available for each device.

Inaccuracy of indicated flowrate "after calibration" (% 4.2 l/h)

These figures expresses the accuracy of observations made by the meter under test for the lowest flow rate set point tested in Phase II, nominally 4.2 litres / hour, the most demanding condition tested. Equivalent figures for higher flow rates will be lower, that is they will reflect better accuracy. The term "after calibration" means that these results imply that the flow meter has been procured and fitted to a test rig and the manufacturers quoted conversion factors to translate the sensed observation (voltage, counts, frequency, current, etc.) to flow rate have been adjusted to reflect *in-situ* test conditions. The reference flow meter used for this calibration was the dynamometer load cell and calibration jig, configured as a mass balance. Data from up to two repeat tests are available for each device.

Inaccuracy of indicated flowrate "out-of-the-box" (% FS)

These figures report the root-mean-square of the disparity between the reference flow rate and the device indicated flow rate, expressed as a percentage of the device's full scale range, computed over all flow rate set points for a test on a given device. The term "out-of-the-box" means that these results imply that the flow meter has been procured and fitted to a test rig without any consideration given to calibration of the device *in-situ*. The manufacturers quoted conversion factors to translate the sensed observation (voltage, counts, frequency, current, etc.) to flow rate are trusted. Data from up to two repeat tests are available for each device.

Inaccuracy of indicated flowrate "after calibration" (% FS)

These figures report the root-mean-square of the disparity between the reference flow rate and the device indicated flow rate, expressed as a percentage of the device's full scale range, computed over all flow rate set points for a test on a given device. The term "after calibration" means that these results imply that the flow meter has been procured and fitted to a test rig and the manufacturers quoted conversion factors to translate the sensed observation (voltage, counts, frequency, current, etc.) to flow rate have been adjusted to reflect *in-situ* test conditions. The reference flow meter used for this calibration was the dynamometer load cell and calibration jig, configured as a mass balance. Data from up to two repeat tests are available for each device.

Observed repeatability (l/h) (Standard deviation @ 25% FS)

These figures indicate the standard deviation of the indicated flow for a flow rate set point equivalent to 25% of a flow metering device's full scale flow rate (rated flow rate). It is found by interpolating between the standard deviation figures for test set points that bracket the 25% full scale flow level.

Observed repeatability (l/h) (Standard deviation @ 75% FS)

These figures indicate the standard deviation of the indicated flow for a flow rate set point equivalent to 75% of a flow metering device's full scale flow rate (rated flow rate). It is found by interpolating between the standard deviation figures for test set points that bracket the 75% full scale flow level.

Phase III section

Inaccuracy of indicated flowrate "out-of-the-box" (% 4.6 l/h)

The disparity between observations made by the meter under test and corresponding reference flow rates provided by the FMS1000 as a percentage of the reference flow rate, at the test set point corresponding to a nominal flow rate of 4.6 litres / hour. In general, equivalent figures for lower flow rates will be higher, that is they will reflect poorer accuracy; equivalent figures for higher flow rates will be lower, that is they will reflect better accuracy. This flow rate set point has been selected so that the figures in this row (for Phase III) can be compared with those in the first row of the Phase II section of Table 32. The term "out-of-the-box" means that these results imply that the flow meter has been procured and fitted to an engine without any consideration given to calibration of the device *in-situ*. The manufacturers' quoted conversion factors to translate the sensed observation (voltage, counts, frequency, current, etc.) to flow rate are trusted. Data from three repeat tests are available for each device.

Inaccuracy of indicated flowrate "after calibration" (% 4.6 l/h)

The disparity between observations made by the meter under test and corresponding reference flow rates provided by the FMS1000 as a percentage of the reference flow rate, at the test set point corresponding to a nominal flow rate of 4.6 litres / hour. In general, equivalent figures for lower flow rates will be higher, that is they will reflect poorer accuracy; equivalent figures for higher flow rates will be lower, that is they will reflect better accuracy. This flow rate set point has been selected so that the figures in this row (for Phase III) can be compared with those in the second row of the Phase II section of Table 32. The term "after calibration" means that these results imply that the flow meter has been procured and fitted to an engine and the manufacturers' quoted conversion factors to translate the sensed observation (voltage, counts, frequency, current, etc.) to flow rate have been adjusted to reflect *in-situ* test conditions. The reference flow meter used for this calibration was the dynamometer load cell and calibration jig, configured as a mass balance (N.B. the Phase II calibration co-efficients have been used again in Phase III). Data from three repeat tests are available for each device.

Inaccuracy of indicated flowrate "out-of-the-box" (% FS)

These figures report the root-mean-square of the disparity between the reference flow rate and the device indicated flow rate, expressed as a percentage of the device's full scale range, computed over all flow rate set points for a test on a given device. The reference flow rate is provided by the FMS1000 system. The term "out-of-the-box" means that these results imply that the flow meter has been procured and fitted to an engine without any consideration given to calibration of the device *in-situ*. The manufacturers' quoted conversion factors to translate the sensed observation (voltage, counts, frequency, current, etc.) to flow rate are trusted. Data from three repeat tests are available for each device.

Inaccuracy of indicated flowrate "after calibration" (% FS)

These figures report the root-mean-square of the disparity between the reference flow rate and the device indicated flow rate, expressed as a percentage of the device's full scale range, computed over all flow rate set points for a test on a given device. The reference flow rate is provided by the FMS1000 system. The term "out-of-the-box" means that these results imply that the flow meter has been procured and fitted to an engine without any consideration given to calibration of the device *in-situ*. The term "after calibration" means that these results imply that the flow meter has been procured and fitted to an engine and the manufacturers' quoted conversion factors to translate the sensed observation (voltage, counts, frequency, current, etc.) to flow rate have been adjusted to reflect *in-situ* test conditions. The reference flow meter used for this calibration was the dynamometer load cell and calibration jig, configured as a mass balance (N.B. the Phase II calibration co-efficients have been used again in Phase III). Data from three repeat tests are available for each device.

Observed repeatability RMS Standard deviation (l/h)

These figures report the root-mean-square of the standard deviation of the 20 second average flow rates indicated by the flow meter under test, taken across all set points of a test run. Data from three repeat tests are available for each device. These figures reflect uncertainty arising from the flow rate sensing system as a whole (i.e. including channel transmission and data acquisition), not just those arising from the flow meter device under test.

Observed repeatability of FMS1000, RMS Standard deviation (l/h)

These figures report the root-mean-square of the standard deviation of the 20 second average flow rates indicated by the FMS1000 fuel weigher that provides the reference flow rates for each set point, taken across all set points of a test run. These figures reflect uncertainty arising from the reference flow rate sensing system as a whole (i.e. including channel transmission and data acquisition), not just those arising from the FMS1000 alone. Data from three repeat tests are available for each device. In general, it is to be expected firstly that these figures should be low, indicating the high accuracy and precision of the FMS1000 unit and, secondly, more or less the same value reported across all test repetitions of all devices indicating that consistent methodology and experimental conditions prevailed across all the tests.

Average uncertainty relative to FMS1000

These figures report the ratio of the Observed repeatability of the fuel meter under test to the Observed repeatability of the FMS1000. This measure attempts to quantify the uncertainty of flow rate observations taken by the meter under test relative to the uncertainty of flow rate observations taken by the FMS1000. Values at or around 1 indicate that the flow meter under test provided observations of similar uncertainty to those returned by the reference device (the FMS1000) for the same experimental conditions. Values >1 indicate that the meter under test compares poorly with the FMS1000 for the same experimental conditions.

General Observations across all devices

The observed repeatability values for the FMS1000 reference fuel weigher are all low, confirming high precision observations from this instrument, and the values are all broadly consistent across all devices under test and all tests for each device (0.03-0.04 l/h). The highest value (indicating the worst repeatability of the reference system) occurs for the first test of the Emerson CMF025M (0.05 l/h).

"Out-of-the-box", the accuracies of the Oval MIII Flowmate, Macnaught M1 and Floscan 65000 expressed as a percentage of the indicated flow rate has deteriorated from Phase II tests to Phase III tests. For the Emerson CMF025M and the Kobold DRZ this accuracy was better for the Phase III tests than the corresponding results for Phase II.

For Phase III testing on the test engine, the accuracies of the meters expressed as a percentage of the indicated flow rate all improve through calibration.

The accuracies of the meters expressed as a percentage of the full scale rating of the respective devices all improve through calibration, with the exception the Emerson CMF025M Elite.

Some care must be applied when considering figures for accuracy expressed as a proportion of the full scale range of the devices. This is because the full scale rating varies significantly across the range of devices under test. This measure favours meters with a large full scale range, e.g. Kobold DRZ and the Emerson coriollis meter, although the latter is assessed with a turn down ratio of 50 applying.

The repeatabilities of the Oval MIII Flowmate and the Kobold DRZ are comparable to those of the FMS1000 for the conditions of the Phase III tests. The repeatability of the Emerson CMF025M compares well, but not as well as the first two devices mentioned. The repeatability of the Macnaught M1 is variable, for the Phase III tests, despite impressive performance in this respect during the Phase II tests. The repeatability of the Floscan 65000 device is poor compared with the other devices tested and the FMS1000.

Device Ranking

The data presented in Table 33 was used to rank the devices; rank 1 was awarded to the best performer, rank 5 was awarded to the poorest performer. The sum of rankings against each measure of performance was computed, and this was used to rank the devices overall, for Phase II testing and Phase III testing (Table 33).

Table 33: Flow meter device ranking

Device	Test	Oval Flowmate MIII	Macnaught M1	Kobold DRZ	Floscan C/M 65000	Emerson CMF025M Elite
Meter Type		Oval gear	Oval gear	Oscillating piston	Turbine meter	Coriollis meter
Quoted accuracy (%FS, unless specified)		0.50%	0.50%	1.00% (of observation)	Not reported	
FSD flowrate (l/h)		100	100	420	Not reported	2180 kg/h
Cost (£)		£185	£263	£258	£583	£3000-£4000
PHASE II						
Inaccuracy of indicated flowrate "out-of-the-box" (% 4.2 l/h)		1	2	3	4	5
Inaccuracy of indicated flowrate after calibration (% 4.2 l/h)		2	1	5	3	4
Inaccuracy of indicated flowrate "out-of-the-box" (%FS)		1	2	4	3	5
Inaccuracy of indicated flowrate after calibration (%FS)		1	1	5	4	2
Observed repeatability (l/h) (Standard deviation @ 25% FS)		1	3	5	4	2
Observed repeatability (l/h) (Standard deviation @ 75% FS)		2	3	5	4	1
Ranking score		8	12	27	22	19
Overall Rank		**1**	**2**	**5**	**4**	**3**
PHASE III						
Inaccuracy of indicated flowrate "out-of-the-box" (% of 4.6 l/h)		1	2	3	5	4
Inaccuracy of indicated flowrate after calibration (% of 4.6 l/h)		3	1	2	5	4
Inaccuracy of indicated flowrate "out-of-the-box" (%FS)		2	3	1	5	4
Inaccuracy of indicated flowrate after calibration (%FS)		3	2	1	5	4
Observed repeatability RMS Standard deviation (l/h)		1	4	2	5	3
Observed repeatability of FMS1000, RMS Standard deviation (l/h)						
Average uncertainty relative to FMS1000		2	5	1	4	3
Ranking score		12	17	10	29	22
Overall Rank		**2**	**3**	**1**	**5**	**4**

In both Phase II and Phase III, the Oval Flowmate MIII is the best all round performer, the Macnaught M1 performs very well, and the Floscan 65000 and the Emerson CMF025M Elite both perform poorly.

It is suspected that the reason for the relatively poor performance of the Emerson CMF025M is the fact that it is physically rated for a much higher flow rate than any of the other devices, but its instrumentation was set to a turn down ratio of 50 by the supplier, for the purposes of this work. If the device's physical full scale range were considered, then for the Phase II tests, the accuracy expressed as a percentage of full scale would be 0.013%, the best of all meters, by an order of magnitude. For the Phase III tests, the revised accuracy found, expressed as a percentage of physical full scale, ranges between 0.048% and 0.049%; again, the best found across all the meters. Thus, it is very clear to the project team that much better performance of this type of flow meter should be expected if a device with a physical rating closer matched to the range of test and engine fuel flow rates is used.

The reason for the poor performance of the Floscan Cruisemaster 65000 is unknown, although the Phase II testing indicates a linear response and consistent behaviour of the inaccuracies across the two Phase II tests. Poor, and consistent, behaviour of this device is evident across the three Phase III trials. It should be noted that in testing this fuel metering sensor, the manufacturer's supplied data processing / display unit was not used. Rather, the analogue signal of the device as relayed to the Data Track 284 as was the case for the other devices. It is possible that the manufacturer's data processing / display unit has 'on-board' corrections for some of the non-linearity and inaccuracy that is evident in the results presented.

The surprise in the Phase III testing is the performance of the Kobold DRZ; the rank for this device has increased from 5th to 1st between Phase II and Phase III.

Taking Phase II and Phase III performance together, the final ranking of the metering devices is as follows:

1st .Oval MIII Flowmate
2nd Macnaught M1
3rd Kobold DRZ
4th Emerson CMF025M Elite
5th Floscan Cruisemaster 65000

Despite best performance in Phase III tests, the Kobold DRZ is finally ranked 3rd because this was not consistent behaviour with the Phase II tests.

Practical considerations for fishing vessel skippers considering installing a meter

1) On the basis of the results we have obtained using the device we were supplied with by the manufacturer, we would not recommend procuring the Floscan Cruisemaster 65000 fuel flow meter. This is despite the fact that of all the devices we have tested, the Floscan product seems to be the only one that is fully complete in the equipment supplied for the £583 price.
2) We would recommend procurement of one of the two oval gear meters we have tested which performed well in both our 'laboratory conditions' tests and our 'on engine' tests.
3) We have less certainty regarding the Kobold DRZ device as it performed very poorly in our 'laboratory conditions' tests, yet performed the best when installed on our test engine.
4) We think that the Emerson CMF025M Elite coriollis flow meter was improperly rated to the flow conditions we tested with, and that much better performance of this type of meter would have been obtained with a device not operating with a turn-down ratio of 50 – as ours was.
5) For larger fuel consumption rates than the 25 litres/hour consumption rate of our test engine, a coriollis meter could well be a sensible choice, especially if there is an appreciable return flow to the tank from the engine (as is the case with Cummins engines, for example), or there is a mixture of fuel vapour and liquid fuel in the return fuel lines. As coriollis meters measure the mass flow rate, there would be no need to account for these different phases of fuel in special ways, nor would there be a need to apply a temperature correction to the return fuel flow, as when there is appreciable return fuel, it also, typically, has higher temperature and thus its volume will have increased. The positive displacement meters and the Floscan meter would all need temperature correction for the return flow in these conditions, meaning that means of monitoring the return fuel temperature would also be required.
6) With fuel metering sensors that are not sold packaged with remote monitoring display consoles, eventually, we were impressed with Data Track 284 unit that we procured for this work, which can be supplied in a version using a 24V DC supply. Skippers entertaining installing either of the oval gear meters or the oscillating piston meter will need to additionally procure a device like the Data Track that can convert the frequency of rotation or oscillation of the meter into units of flow that can be displayed on the bridge. The Data Track 284 can handle 2 flow meter inputs, can display in scaled units of choice and can log real time data to a computer, if required.
7) We would recommend installing the fuel meter in the fuel lines with by-pass legs, in case of blockage of the fuel meter, with the oval gear meters and the Kobold DRZ. Opportunities for blockages are reduced if the meter on the feed line is installed after the fuel filter.

8) As well as the Floscan, there are other 'turn-key' solutions available on the market for real time fuel flow monitoring, for example that available from KRAL (http://www.kral.at/en/engines/?L=2). We would suggest giving serious consideration to having the fuel meter supplier installing the unit on board as part of a supply contract.
9) We saw that the performance of all the meters we tested improved once they had been calibrated. In practice this meant that the factor supplied by the manufacturer to convert the sensed quantities (for example, voltage, current or frequency) to flow rate units was a little 'off'. We would thus further suggest that a calibration procedure be additionally included in the supply contract, supported by a manufacturers' calibration certificate. It would be useful for skippers to check this calibration in the operational environment, but in doing so, one would have to make sure that great care was taken in measuring volumes, temperatures and densities of fuel at the times of fill up as it will be quite difficult for skippers to improve on sensor calibration procedures conducted in a laboratory, or in a manufacturer's quality assurance department.
10) When comparing specifications for the expected performance of fuel metering systems that you are planning to procure, ensure that:
    a. The full scale range of the meter suits the flows on your engine, remembering that for some engines, the return flow to the tank could be much greater than the fuel consumed by the engine.
    b. You have also considered the accuracy that the device will return as a percentage of the observation made, rather than as a percentage of the full scale range, for the lowest flow rates you expect (engine idling conditions). Manufacturers most frequently quote accuracy as a percentage of the full scale range.
    c. The sensitivity of the channel relaying the sensor signal to the vessel bridge is well matched to the accuracy and repeatability of the sensor.

Conclusions

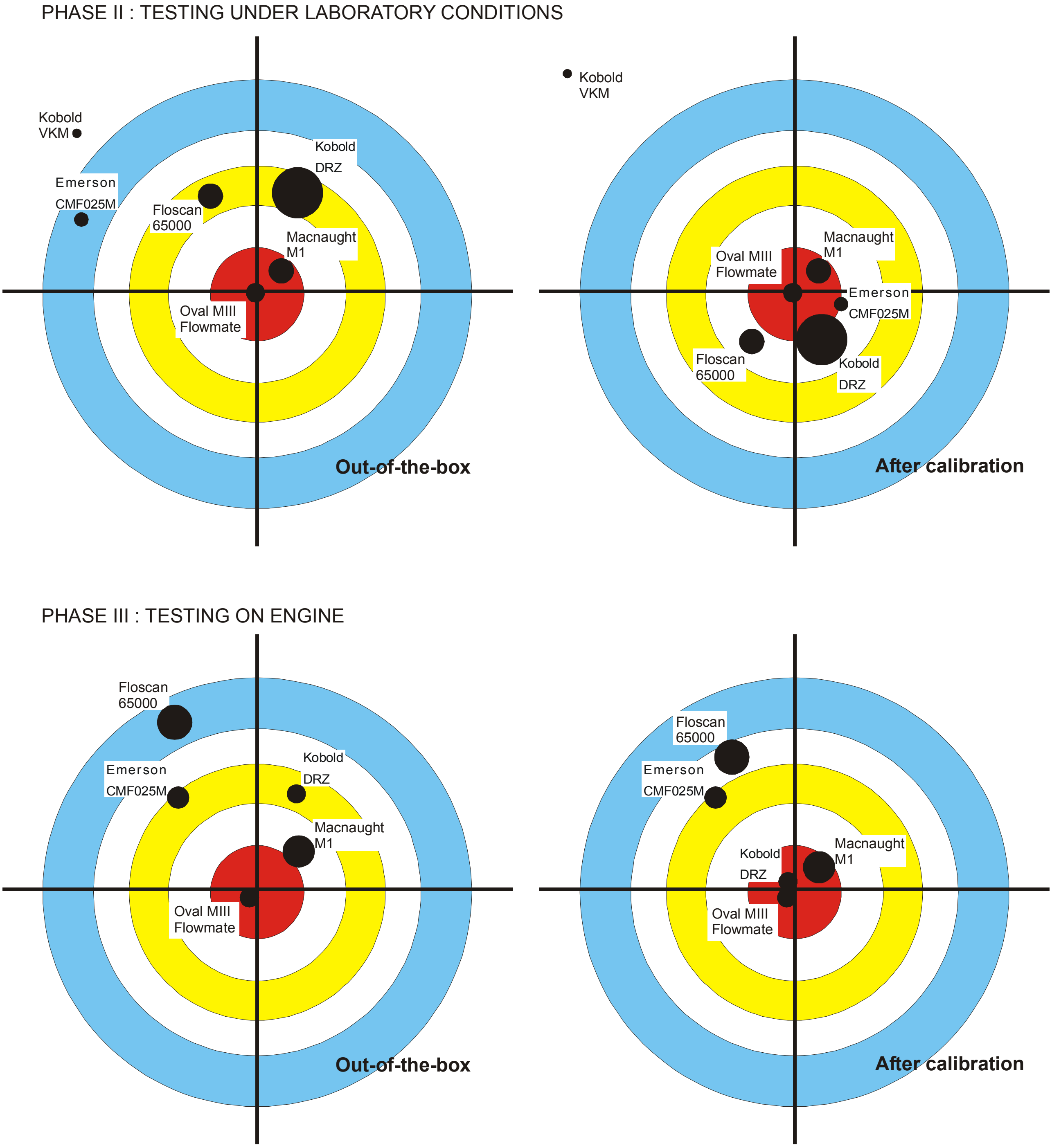


Figure 26: Relative performance of devices using the target analogy

The 'target analogy' introduced in the Phase II report is revisited to graphically indicate the relative performance of the fuel flow measurement systems incorporating the flow meters under investigation. On the targets, the distance of the centre of the circle for a given meter represents the accuracy of the device, the size of the circle represents the repeatability of observations. The LHS target shows the relative situation before calibration of the devices, the RHS target shows the same, after calibration. The upper targets reflect the Phase II investigations, the lower targets reflect the Phase III investigations.

The lower RHS target of the diagram (Figure 29) illustrates that it is possible to use three of the five meters subjected to testing in Phase III in an effective fuel metering role for the CSM Engine Dynamometer test cell engine. It is believed that the full scale flow rating of the Emerson CMF025M used with a turn down ratio of 50 would make it unsuitable for fuel metering on the CSM Engine Dynamometer test cell engine. The reason for the poor performance of the Floscan fuel meter is unknown.

At the end of Phase II of the overall study, it was stated that the essential distinction between the fuel meters and their measurement systems reduced to considerations of the ease of undertaking a calibration exercise on a working fishing vessel. According to the Phase III results, the Oval MIII Flowmate device is likely to produce valid observations of fuel flow without requiring calibration *in situ*. For this reason, it is our favoured fuel meter.

The objective for the Phase III work, stated at the end of the Phase II report was stated as needing to investigate whether the relative rank of any particular sensing device changes when the meter is installed on an engine and subjected to, for example, vibration and pulsating flows. The following listing addresses this objective:

Device	**Change when operating on a working engine**
Oval MIII Flowmate	Slightly lower accuracy and repeatability
Macnaught M1	Slightly lower accuracy and repeatability
Kobold DRZ	Much improved accuracy and precision
Emerson CMF025M	Slightly lower repeatability, lower accuracy
Floscan Cruisemaster 65000	Lower repeatability and lower accuracy

In making this assessment, we have used figures for accuracy applying after calibration of the sensors has been undertaken.