

CRANFIELD UNIVERSITY

ALUN LEWIS THOMAS

**METERING PRACTICE AND POLICY: AN EXAMINATION OF
BATTERY ELECTROMAGNETIC METER CALIBRATION,
PERFORMANCE AND VERIFICATION**

SCHOOL OF ENGINEERING

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Supervisor: Professor H C Yeung

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**This thesis is submitted in partial fulfilment of the requirements for the
degree of Doctor of Philosophy**

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To Andrzej Klos
and
Alfred Brameller

ABSTRACT

The last twenty years has seen the rise to dominance of electromagnetic flowmetering (EFM) technology within the UK water industry network. In the last ten years, the introduction of battery powered EFM designs, for both full bore and insertion meters has seen this technology deployed where before only mechanical meters were used. Nevertheless, despite the increasing use of battery meters, the literature contained little objective reporting of the performance, limitations, calibration or verification of this new technology; in part due to a market monopoly by the original UK developer.

This thesis therefore sets out to examine the performance of this battery EFM design both in full bore and probe formats, and to understand the importance of performance differences between it and existing metering: as relevant to the UK regulatory policy and reporting framework and individual water company water balance submissions.

Following initial laboratory work, effort was directed to gathering site data. Two applications were examined: (a) the use of insertion probes as part of a meter verification programme overseen by the Environment Agency (EA); (b) the application of full bore battery EFM meters in a Small Area Monitor (SAM) supplying regulatory water balance data. Each augmented the baseline performance, calibration and data quality assessments made in the initial laboratory experiments.

Pursuance of the battery probe work led to the creation of integrated, field based profiling/verification software meeting EA requirements. This allows for real time, objective and comprehensive velocity measurements; incorporating assessment of data quality, the ability to approve/reject readings, visualisation of the velocity profile plus on-site calculation of the profile factor and multiple mean velocity points.

Limitations concerning probe use and maximum flow velocities were investigated, showing that the published limits are significantly optimistic. This has important practical implications and testing on a 1200mm pipe confirmed that large errors can result, unless derating factors are applied to the manufacturer's velocity limits. Work on probe errors due to angular misalignment, yaw, showed that compared to mechanical alternatives the battery probe shows relatively smaller errors.

Performance of the full bore meter in the medium term was investigated by excavating a 6 year old buried SAM meter. This revealed a significant, generic failing in the calibration of the battery technology such that all meters produced up to that point are in error at low flows, overestimating the SAM supply volume by between 0.5% and 1.5%.

The thesis demonstrates that, within the limits of the experimental methods employed, not all published performance claims concerning battery EFM meters could be rigorously defended.

Overall the thesis shows that, in order to assure the quality of regulatory data, significant changes to battery EFM factory calibration, field profiling/verification procedures and regulatory policy are needed.

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NOTATION

List of Symbols

Symbol	Description	Units
B	Magnetic flux density	T - tesla
D	Pipe diameter internal	m - metres
d	Probe or rod external diameter	m
E	Voltage generated between electrodes	V - volts
F_{critical}	Critical vortex shedding frequency	Hz
F_{REQ}	Frequency of probe vibration external to pipe	Hz
F_{REQ}	Frequency of probe vibration internal to pipe	Hz
f_f	Pipe friction factor	dimensionless
F_i	Probe insertion factor	dimensionless
F_p	Profile factor	dimensionless
F_v	Vortex shedding frequency	Hz
K	Manufacturer's insertion factor equation constant	dimensionless
L_{ext}	Length of unsupported probe length external to pipeline	m
$L_{\text{ins-uns}}$	Length of unsupported probe length inserted into pipeline	m
m	Von Karman factor	
Q	Volumetric flow rate	m^3/s
R	Pipe internal radius	m
Re	Reynolds number	dimensionless
r	Point radius corresponding to u	m
S	Flow meter sensitivity	dimensionless
St	Strouhal number	dimensionless
U	Uncertainty	
U_c	Expanded uncertainty	
u	Point velocity	m/s
u_{max}	Maximum velocity	m/s
u_{mean}	Mean or average velocity	m/s
ν	Kinetic viscosity	m^2/s
y	Probe insertion depth	m
C_i	Customer and other demand components	m^3
DI	Distribution input	m^3
μ_i	Individual demand component estimates	m^3
μ_D	Individual DI component estimates	m^3
σ_i	Standard deviation of demand components	
σ_D	Standard deviation of DI components	
$F_R(\nu_i, \nu_D)$	Likelihood function for C_i	
λ	Lagrange multiplier	
ν_i	MLE adjusted demand component	m^3
ν_D	MLE adjusted DI component	m^3

Abbreviations

A2D	Analogue to Digital
D2A	Digital to Analogue
D/S	Down Stream
D of E	Department of the Environment
DCM	Domestic Consumption Monitor
DI	Distribution Input
DMA	District Metering Area
DTI	Department of Trade and Industry
EA	Environment Agency
EEPROM	Electrically Erasable Programmable Read-Only Memory
EFM	Electromagnetic Flow Meter
FLOMIC	Flow Measurement and Instrumentation Consortium
FLOWMECO	International Flow Measurement Conference
GV	Gate Valve
GSS	Guaranteed Standards Scheme
I/O	Input/Output
ICA	Instrumentation, Control and Automation
ICS	Interim Completion Statement
IIUA	International Instrument Users Association
IPTS	Insertion Probe Transfer Standard
JR	June Return
KPI	Key Performance Information
LoS	Levels of Service
MF	Meter Factor
MLE	Maximum Likelihood Estimation
MM	Master Meter
MPE	Maximum Permissible Error
MUT	Meter Under Test
NEL	National Engineering Laboratory
NRA	National Rivers Authority
NRW	Non Revenue Water
NSE	Normalised standard error
NWML	National Weights and Measures Laboratory
OFWAT	Office of Water Services

PC	Portable Computer
PRV	Pressure Reducing Valve
PWS	Public Water Supply
Qn	Nominal flowrate
QR	Quarterly Report
Qt	Transitional flowrate
SAM	Small Area Monitor
SD	Standard Deviation
SEPA	Scottish Environmental Protection Authority
SoS	Standards of Service
STW	Severn Trent Water
SVI	Static Verification Instrument
TCU	Total Customer Use
TWD	Total Water Delivered
U/S	Up Stream
UCV	Unmeasured Customer Volume
UFW	Unaccounted For Water
UKAS	UK Accreditation Service
UKWIR	UK Water Industry Research
W	Weight function
WB	Water Balance
WIB	Dutch member of IIUA
WICS	Water Industry Commission for Scotland
WIS	Water Into Supply – summated volume
WISPY	Water Into SuPply – meter description

1. INTRODUCTION

1.1 OBJECTIVES OF THE RESEARCH

The primary aim of the research presented in this thesis has been to address the performance, calibration, verification and limitations of battery powered electromagnetic (EFM) meters.

In parallel, work was undertaken on the development of software tools suitable for regulatory application and principally focused on meter verification using battery insertion probes. These tools aimed to facilitate better regulatory scrutiny of meter verification and improve the quality of field results.

The composite intention has thus been to better understand battery powered EFM metering applications and to improve confidence in the quality of data being submitted for regulatory purposes.

Together, the separate research strands have: (1) led to recommendations covering all aspects of the battery EFM technology; (2) indicated improvements to regulatory policy and (3) provided greater understanding of the quality of regulatory battery EFM data, as used in the determination of water network balance calculations.

1.2 BACKGROUND TO THE RESEARCH

In the mid 1990's, Severn Trent Water (STW) began a number of large capital investment schemes linked to improving the quality of the flow data submitted to industry regulators[1]. The use of EFM meters to replace earlier generations of differential pressure and mechanical meters was central to these metering initiatives. Within the distribution network this created opportunities for battery powered versions of the EFM technology, many of which were buried. Similarly, the traditional turbine insertion meter used widely as a measurement device in the water distribution network was replaced by a battery electromagnetic version having no moving parts.

As part of the same investment programme a separate system of verifying important meters was undertaken, initially to accommodate the needs of the National Rivers Authority (NRA), which later became part of the Environment Agency (EA).[2] This required that all meters classified as "source and strategic" meters were to be checked for accuracy, in situ. These meters principally included major abstraction meters plus those measuring the output of treatment works, i.e. those meters of importance in regard to providing flow data to the regulatory authorities comprising the EA and the Office of Water Services (OFWAT). Some years later, in the earlier 2000's, the scope of verification was extended to include the buried battery powered meters operating within the distribution network.

From this verification work it became clear that not only was it essential to standardise on verification procedures and methodology, but that in respect of several important

areas there were gaps in the knowledge of EFM performance and calibration, pertinent to delivering reliable, traceable and repeatable regulatory data of assessed accuracy and uncertainty.

By 2001, due to the nature of the instrumentation market, the battery powered EFM meter technology chosen for examination in the thesis had been developed by only one manufacturer. Nevertheless, the design approach adopted by ABB was of itself generic and it was predicted that the technology would be taken-up by other global manufacturers. This has been the case, with two other meters now competing in 2009.

1.3 RESEARCH DRIVERS

Strategic Driver linked to Regulation.

The key driver behind the work contained in this thesis is the relationship between aspects of the technology, measurement and regulation of battery EFM meters, as illustrated in figure 1.1.

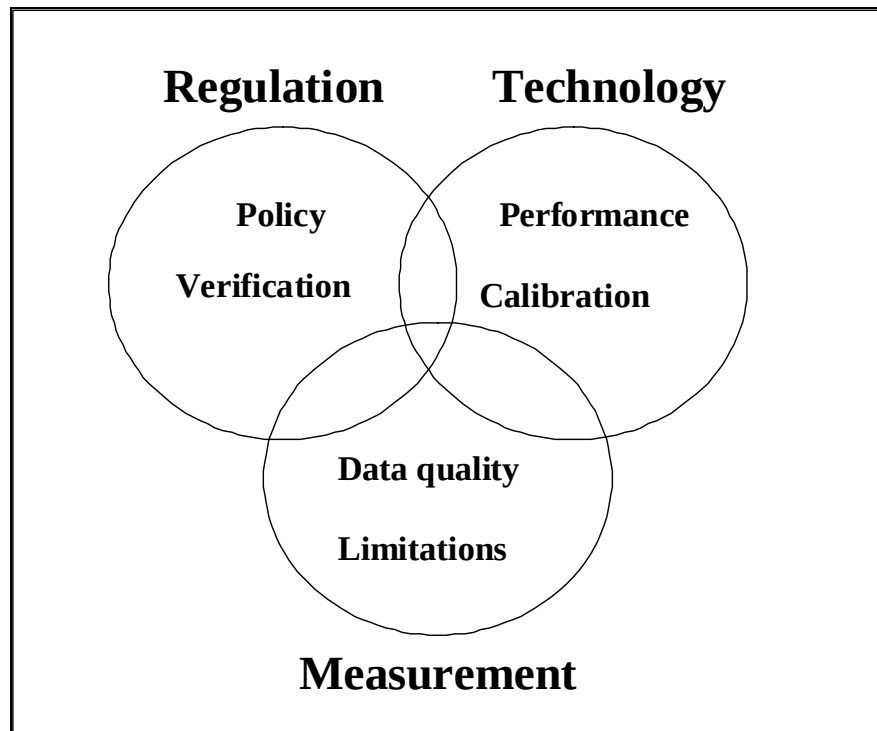


Figure 1.1: Links between EFM meter technology, measurement and regulation

Detailed elements of the research, as described in the individual chapters of the thesis, were directed by the need to examine battery EFM performance, calibration, verification and limitations in relation to practical data quality, which is directly linked to regulatory policy.

Driver: Examination of EFM performance, calibration and limitations.

Of considerable practical importance was the lack of data on performance - which depends upon time-sampled data - from either the manufacturer or from independent

test houses. It appeared to have been assumed that because the theoretical principles underlying the operation of the meter were unchanged, the practical effects of battery powering would be negligible. In view of the importance of much of the flow data which could in future be generated by battery instrumentation, such a position invited investigation.

Because of the supply position, the focus of research had to be placed around the available instrumentation from one single manufacturer, ABB. Two flowmeter models were examined: (1) a full bore battery EFM meter and (2) a similar battery-powered EFM insertion probe meter. Both items shared the same transmitter design which was interchangeable.

Driver: Emulation of water industry specific conditions.

A particular driver behind the laboratory tests was the aim to emulate industrial conditions through the use of realistic pipework configurations, in contrast to previous published work in the area of EFM calibration which had adopted smooth, laboratory pipework atypical of that used in the water industry.

Also of importance in regard to the laboratory test work was the fact that, coincidentally with the start of the research, the EFM sensor design from ABB was changed from full bore – no reduction in diameter across the meter flow tube - to one having a reduced diameter or “throat”, akin to that seen in a classical Venturi construction. The performance and calibration of an EFM meter with this changed physical shape was undocumented and the development prompted an expansion of the original series of tests planned to examine calibration and performance. Subsequently, other manufacturers adopted the reduced bore section design principle, with the result that the laboratory performance testing undertaken on the one model has potentially generic value.

Driver: Establishment of an independent and traceable EFM insertion probe calibration standard.

For the EFM insertion probe, whilst the literature contained much information describing technology independent sources of generic probe error, none was specific to the actual performance and limitations of commercial insertion EFM meters. Of concern therefore was the fact that the calibration of commercial EFM insertion meters had been neglected. A key driver was thus to develop an appropriate independent and traceable probe calibration facility, along with suitable calibration software.

Driver: Benchmarking the quality of EFM insertion meter site performance data.

The lack of knowledge concerning EFM insertion probe calibration further extended to that pertaining to the accuracy of the meter verification field data being collected using the insertion technology. Whilst a mass of historical results from meter verifications using various probes was in existence, the traceability and quality of this archive was undefined. The ability to objectively and critically assess velocity profile site data

therefore became another key focus of the research, with the EA contributing directly to the development of a requirements specification for field profiling.

Driver: Medium term EFM performance, data quality and stability.

Where battery EFM technology is to be adopted in place of mechanical metering there arises the need to assess potential regulatory and technical issues which may arise in the medium, 5 years, to the long term. The particular drivers for a battery powered technology centre around three aspects: (a) the quality of the battery EFM data; (b) the calibration stability of the battery technology and (c) the development of an evidence based case for ongoing meter maintenance and verification requirements; possibly utilising static verification instruments (SVIs).

1.4 TARGETTED RESEARCH OUTCOMES

The desired outcome arising from the individual work elements contained within the thesis is shown in figure 1.2

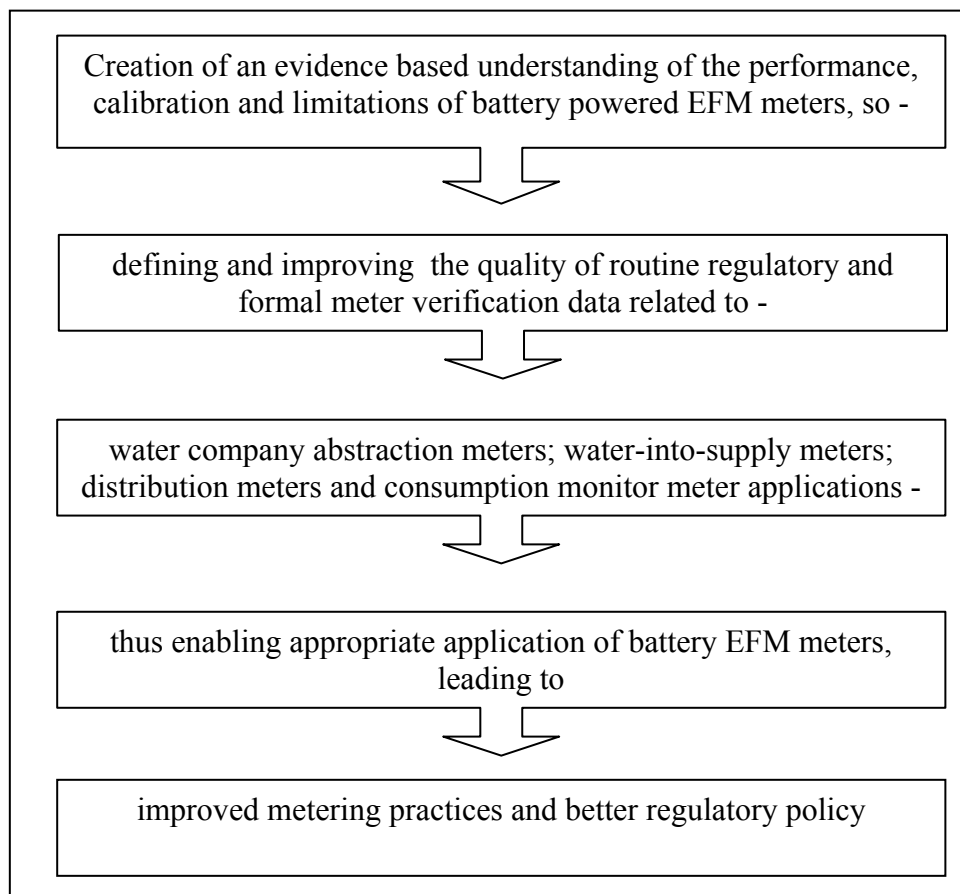


Figure 1.2: Strategic links in developing battery EFM metering practice and policy

As figure 1.2 illustrates, the aim of the research was primarily to determine the performance characteristics, data quality and appropriate application of battery EFM meters, prior to improving metering practice within the context of the current regulatory framework.

To expedite this aim the work was focused broadly into six areas. Within each of these a series of general outcomes were targeted. They were:

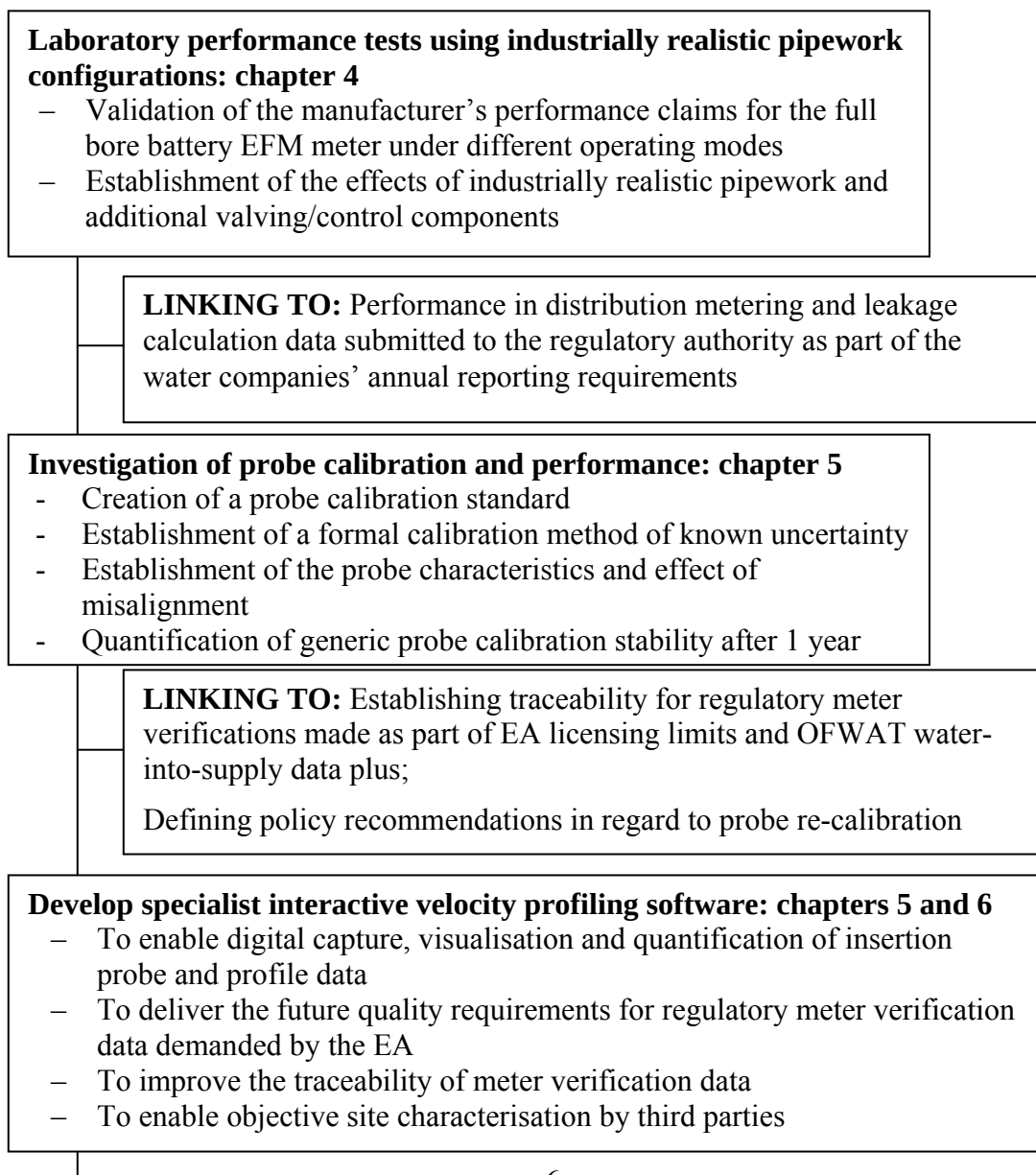
- A. Performance
 - i. Creation of an understanding of the technical performance of both the full bore and insertion EFM meter variants under ideal conditions.
 - ii. Assessment of these general performances in order to create confidence in the validity of the manufacturer's published data.
 - iii. Assessment of the field performance of insertion probes.
- B. Calibration
 - i. Development of suitable methods, including software, to accurately calibrate the battery EFM designs.
 - ii. Creation of a standardised approach to the calibration of EFM probes, including development of a hardware standard, associated software and data analysis.
- C. Limitations
 - i. Knowledge of the battery EFM meter under non-ideal conditions, focusing specifically on typical industrial, water industry, installation configurations.
 - ii. Determination of the effect of excitation mode on calibration and performance; including that when using a battery EFM probe to measure the velocity profile in a pipe.
 - iii. Determination of the effect of flow velocity on insertion probe vibration and thus performance.
- D. Verification
 - i. Development of suitable software to accurately record and assess site velocity profiles.
 - ii. Determination of the practical performance and level of repeatability, which may be achieved when profiling a meter verification site.
- E. Data Quality
 - i. Development of appropriate recording and analysis tools to assess battery EFM data both in the laboratory and in the field.
 - ii. Establishment of the spread of uncertainty associated with battery EFM meter applications.
 - iii. Demonstration and assessment of inter-laboratory probe calibration.

Policy

- iv. Identification of the improvements to the methodology of velocity profiling to deliver verification reports which are reliable, repeatable, traceable and auditable. This was a generic requirement, which included application of the battery EFM technology.
- v. Scoping of future regulatory assessment needs for battery EFM meters by analysis of the performance of a batch of 5 year old meters.
- vi. Identification of the application areas where battery EFM meter performance will have an impact on regulatory policy and the calculation of water network balance.

1.5 OVERVIEW OF THE MAJOR WORK ITEMS

An overview of the practical work, established to deliver the targeted outcomes described, is summarised in the following flow diagram. This shows the links between the different areas of study and the regulatory framework. It generally follows the sequence of chapters but the block items necessarily contain overlapping elements.



LINKING TO: The creation of standardised regulatory meter verification test records; capable of forming a consistent, standardised, inter-company archive of verification data able to satisfy EA/OFWAT meter verification data needs

Establish baseline probe profiling performance: chapter 5

- To create knowledge of baseline data quality achievable in the laboratory and establish benchmark statistics
- To demonstrate long term stability of the calibration facility
- To investigate re-calibration performance of probes
- To assess and quantify verification performance in optimum conditions prior to site determinations

LINKING TO: Ongoing quality assurance of all regulatory meter verifications;
Establishing historic, traceable records capable of independently conforming to water balance Table 10 data and license returns;
Providing consistent records for use by those auditing the water company verification processes

Undertake probe tests at manufacturer: chapters 5 and 6

- To assess and quantify differences in calibration techniques and results
- To examine probe performance in large pipes, >1000mm, under controlled conditions

LINKING TO: Establishing the validity of the manufacturer's production calibrations;
Cross referencing the Hams Hall traceable standard;
Investigating probe vibration limitations and validating the manufacturer's application recommendations

Undertake velocity profiling/meter verification field trials: chapter 6

- To investigate battery EFM excitation mode influences
- Establish the practical limits of velocity profile reproducibility
- Benchmark the limits for achievable and for practical data quality
- Record a series of site verifications using the software developed
- Analyse the site datasets to understand and quantify the spread of typical verification results

LINKING TO: Regulatory reporting of meter verification which are associated with OFWAT's "June return Table 10" data for distribution input (DI); leakage and consumption components

Investigation of installed performance of battery EFM meters over the medium term: chapter 7

- Determination of data quality from 96 battery EFM meters after 5 years
- Measurement of battery EFM calibration accuracy and stability after 5 years
- Assessment of the regulatory and policy impacts in regard to : maintenance; data accuracy and quality; data integrity and meter calibration

LINKING TO: Regulatory requirements in regard to the accuracy and long term control of battery and buried EFM meters; as well as ongoing "Table 10 June Return" data

2 WATER INDUSTRY HISTORY, REGULATION AND DATA QUALITY ASSURANCE

OBJECTIVE

This chapter places the technical work pursued within the thesis in context. It outlines the recent history of the UK water industry and the importance of meter data quality in implementing statutory regulation of the present private water companies.

OVERVIEW

The formal assessment of regulatory flow data is outlined and the importance of quantifying the quality of measurements is emphasised. Examples are provided to illustrate the sensitivity of component parts of the water balance and the need to choose appropriate metering technology. The role of data monitors and the options for meter verification are explained. The importance of meter performance, meter calibration, meter verification and measurement traceability in underpinning regulatory policy is highlighted, together with those aspects requiring investigation.

2.1 WATER INDUSTRY HISTORY

2.1.1 Pre 1974 local government act and pre-1989 water industry privatisation

In the last 40 years there have been two significant changes to the water industry within the UK. Prior to the 1974 Local Government Act [3] the bodies responsible for water matters, both potable and dirty, comprised local and county councils. These were classed generically as water boards. The 1974 Local Government Act reorganisation of the industry transformed this fragmented structure creating a series of statutory water authorities.

Underpinning the creation of the water authorities was the concept of integrated river basin management. This used natural geography to set organisational boundaries, meaning that the river catchments delineated one water authority from another. Put simply, which side of the hill the rain fell determined which authority took responsibility for the associated river, surface water and ground water resources.

These large organisations were multi functional, incorporating responsibility both for the issuing of water abstraction licences whilst at the same time holding responsibility for complying with these same licenses. Essentially, in regard to the provision of water resources and the efficient utilisation of these resources, water authorities were gamekeeper and poacher under the same organisational roof.

2.1.2 Post 1989 privatisation and the establishment of meter verification

Following privatisation of the water industry in 1989 [4], [5] under the direction of the Minister for the Environment, Michael Howard, responsibility for using abstraction licenses passed from the water authorities to the newly created National Rivers Authority (NRA); later subsumed into the Environment Agency (EA). This separated the long standing arrangements whereby the organisation responsible for abstracting river or groundwater, delivering potable water to customers and then treating it before returning it to the river system, had been one and the same.

Following its creation, the NRA began the task of examining, either on its own or in conjunction with the individual water plc's, the abstraction licenses which it had inherited. The corollary was the need to be able to improve the quality of metering data across the water industry and to be able to match the reported volumes with each license. This requirement underpinned the need to establish traceable meter performance and with it to be able to undertake checks on installed meters using a variety of techniques.

Starting on a company by company basis and following the audit and upgrading of existing installed meters, the NRA/EA created a requirement to regularly check the performance of those meters linked to the abstraction licences. Generically labelled "verification schemes", the scope of the number of meters being checked became enlarged to include those meters measuring "water-into-supply" (WISPY) volumes. The verification programme remit thus expanded to encompass the area covered by the Water Services Regulatory Authority (OFWAT).[6]

2.2 BACKGROUND TO REGULATION AND THE REGULATORY CYCLE

2.2.1 Water industry drivers

There are three imperatives which are presently driving the UK Water Industry. Each has an impact on issues related to water flow measurement and all are politically, as well as technically, sensitive.

The first driver is that of an increasing demand for water which has substantially increased in the last 15 years. According to the Royal Commission report [7], this has led to a doubling in energy since 1990, attributed to increased pumping activity.

The second driver is that of government, which wishes to reduce per capita consumption to an average of 130 litres per day. [8]

The third and final driver is the large and ongoing capital investment programme which is heavily focused on underground assets. [9]

2.2.2 The regulated sector

In total the regulated UK Water Industry presently comprises 10 water and sewerage service providers, 12 water only suppliers and four other regulated companies. One company, Dwr Cymru, is a "not for profit" organisation. The remaining are private and several are subsidiaries of international organisations.

The industry is regulated differently according to region, with the Office of Water Services (OFWAT) in England and Wales, the Water Industry Commission for Scotland (WICS) in Scotland and the Utility Regulator in Northern Ireland (planned to start from 2010, local politics not withstanding).

OFWAT's duties[10] are to protect customers, promote value, safeguard the future and ensure that companies are able to carry out their statutory responsibilities. Encouraging efficiency, meeting the principles of sustainable development and promoting competition are all also within the remit.

The other side of the water industry is that where it faces the environment not customers and here the role of regulatory body is fulfilled in England and Wales by the Environment Agency (EA)[11]; in Scotland by the Scottish Environment Protection Agency (SEPA)[12] and in Northern Ireland by the Department of the Environment (D of E).[13]

2.2.3 The scope of regulated data and the “June Return”

OFWAT operates a system of regulated data collection organised around the “June Return”, which is an annual statement of activities up to the end of the previous financial year, 31st March, but submitted in June[14].

The June Return reports individually on the performance of each of the water companies and lists forty eight tables of information, supported by comments and with explanations. figure 2.1 illustrates this annual reporting cycle.

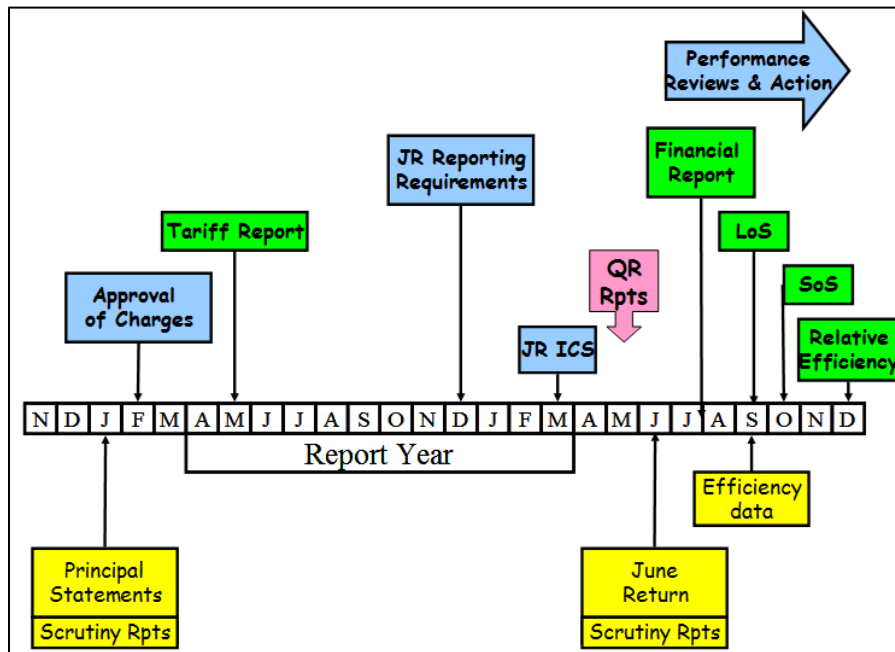


Figure 2.1: The OFWAT annual reporting cycle.[15]

The June return provides specific information in the following areas:

- Key outputs, known formerly as levels of service indicators, e.g. restrictions on water use (hosepipe bans); low pressure; interruption; flooding from sewers; billing complaints; telephone response; meter reading frequency.
- Performance under the Guaranteed Standards Scheme (GSS) and then the relevant area for metering and demand
- Non financial measures, comprising
 - population supplied;

- number of households and non-households receiving measured and unmeasured supplies of water and sewerage services;
 - new connections;
 - meter installations;
 - supplies to non-households;
 - volumes of water affected by various undertakings and relaxations;
 - the volume of water delivered, including leakage;
 - volumes of sewage and effluent collected, treated and disposed;
 - lengths of water mains and sewers inspected, repaired and renewed;
 - water sources;
 - treatment needs;
 - types of water and sewage treatment works.
- (d) Regulatory accounts
(e) Financial measures

2.3 ASSESSMENT AND CERTIFICATION OF WATER BALANCE DATA

Table 10 OF THE JUNE RETURN and DATA GRADING

2.3.1 The June Return Table 10, 10B(i) and Table D

These three tables are the repository for the individual water balance components.

- A) Table 10 details water delivered and is part of “non financial measures”.
- B) Table 10B(i) contains the environment agency data, including abstraction volumes; it is also labelled “non financial measures”.
- C) Table D contains the key water balance and metering summary data; it is labelled “boards overview, water service-key supporting information”.

Examples are shown in Appendix 1, 2, and 3 and are for Severn Trent Water [16].

2.3.2 Confidence grades

A confidence grade system has been established by OFWAT[17] to provide a reasoned basis to qualify information in respect of reliability and accuracy. It consists of an alphanumerical code coupling a reliability letter and an accuracy band.

e.g. data based on sound records would score A2.
 decoded this is: Band A : highly reliable;
 accuracy band : 2, data estimated to be within $\pm 5\%$.

2.3.3 Reliability bands

There are four reliability bands which are applied to data:

A - Highly Reliable:

- Actuals - data based on sound records, procedures, investigations or analysis which is properly documented and recognised as the best method of assessment.

- Forecasts – data based on extrapolations of high quality records covering or applicable to 100% of the company's area, kept and updated for a minimum of five years. The forecast will have been reviewed during the forecast year.

B – Reliable:

- Actuals - as for 'A', but with minor shortcomings e.g. the assessment is old; there is missing documentation; reliance on unconfirmed reports; use of extrapolation.
- **Forecasts** - based on extrapolations of records covering or applicable to more than 50% of the company's area, kept and updated for a minimum of five years. The forecast will have been reviewed during the previous two years.

C – Unreliable:

- Actuals - data based on extrapolation from a limited sample for which grade A or B data are available.
- Forecasts - based on extrapolations of records covering more than 30% of the company's area. The records from which the extrapolations are made must have been kept and updated for a minimum of five years.

D – Highly Unreliable:

- Actuals - data based on unconfirmed reports and/or cursory inspections or analysis.
- Forecasts – data based on forecasts not complying with bands A, B or C.

Note that the “forecasts” category is rarely used once the organisation has been graded for more than a few years. It was created at the beginning of OFWAT’s regulatory regime to enable companies to comply with the June return requirements, whatever the state of their data.

2.3.4 Accuracy bands

These are set by the regulator and are (mis)-termed accuracy bands, not estimates. They are defined as follows:

1. - better than or equal to $\pm 1\%$
2. - better than or equal $\pm 5\%$ - (but not band 1)
3. - better than or equal to $\pm 10\%$ (but not bands 1 or 2)
4. - better than or equal to $\pm 25\%$ (but not bands 1,2 or 3)
5. - better than or equal to $\pm 50\%$ (but not bands 1,2,3 or 4)
6. - better than or equal to $\pm 100\%$ (but not bands 1,2,3,4 or 5)
- X - values outside the matrix scope, such as $>100\%$, or small numbers
- 4 Matrix of Confidence Grades

Together the reliability and accuracy bands form the matrix of confidence grades.

Distribution Input..... (B2),

This leads to an overall water balance grade - B2, for the company.

By way of explanation, note that the water balance reconciles only to within 5% of the distribution input (DI) and therefore attracts a rating of “B”. This contrasts with the individual components which have been estimated separately, with several better than B.

As explicitly stated in the table, 97 % of the volumes associated with the individual components have a reliability band of A or B, principally because they are generated from strategic “water-into-supply” meters which are verified or calibrated on a yearly basis. Nevertheless, overall, the water balance grading remains B.

Severn Trent’s OFWAT matching reliability grading is illustrated in table 2.3:

OfWat Reliability Grades for the Water Balance						
		Grade A	Grade B	Grade C	Grade D	Qualification
1	Unmeasured Household consumption per capita consumption					
	Either - Individual Monitor or Area Monitor					
1.1	Sample representative of houses type etc within Co area	✓				For Grade A : either 1.1 and 1.3 to be ticked, or 1.1 and 1.5 to be ticked
1.2	Sample not representative of house type within Co area		✓			
	Individual Monitor					
1.3.	Cover at least 1000 Props all supplying data (i.e. more than 1000 to be monitored to allow for failure or meter problems	✓				For Grade B: either 1.2 and 1.4 to be ticked or 1.2 and 1.6 to be ticked
1.4	Cover at less than 1000 Props		✓			
	Area monitor					
1.5	50 % of DI to be consumed by unmeasured households. Measured HH <10% and Non HH less than 30%	✓				
1.6	< 50 % of DI to be consumed by unmeasured households. Measured HH >10% and Non HH > 30%		✓			
1.7	Estimation not using a monitor, but from a sample of metered customers or other company's monitor			✓		
1.8	Estimated from the residual of the Water balance or other Co estimates				✓	
2	Unmeasured non-household water delivered (l/p/d)					
2.1	Estimated from Co own monitor of different SIC types	✓				
2.2	Derived from other Co data or own data over two years old		✓			
2.3	Derived from Industry averages or rateable values			✓		
2.4	Estimated from residual of water balance after other components are estimated				✓	
3	Total Leakage (Mild)					
	Using BU leakage . Should reconcile to within 5% of residual from Integrated flow method	✓				Grade A:- All to be ticked .
3.1	Data to represent the average for the year	✓	✓			
3.2	Nightline line estimated with continual monitoring covering > 80 % of props, recorded more than 20 times a year	✓				Grade B either 3.6 or both 3.2 and 3.4 to be ticked.
3.3	Nightline line estimated with continual monitoring covering > 60 % of props, recorded less than 20 times a year		✓			
3.4	Nightline line estimated with continual monitoring covering < 60 % of props, recorded less than 20 times a year			✓		Grade C:- Either 3.5 or 3.8 to be ticked but not 3.9,3.10 or 3.11
3.5	Sample surveys on Service reservoirs and trunk mains	✓				
3.6	Total integrated flow method		✓			Grade D:- Either 3.9 or 3.10 or 3.11 to be ticked.
3.7	Derived from a software package which uses Co own data, national estimates or default values			✓		
3.8	Leakage is residual balance once all other components have been estimated				✓	
3.9	Derived solely from leakage package , not supported by leakage level estimates BU or TD				✓	
3.10	Based on drop tests alone				✓	
3.11						
4	Distribution Input (Mild)					
4.1	Sum of Components to reconcile within 2% of DI	✓				Grade A:- All of 4.1,4.5 and 4.8 to be ticked
4.2	Sum of Components to reconcile within 5% of DI but not within 2%		✓			
4.3	DI taken from Water into supply meters and does not reconcile within 5% of sum of components			✓		Grade B:- All of 4.2,4.6 and 4.8 to be ticked but not 4.9
4.4	Taken from Water into supply meters only and adjustments made without reference to other components				✓	
4.5	DI estimated from Water into supply meters which record 95% of DI	✓				Grade C:- All of 4.3,4.8 and 4.9 to be ticked but not 4.4
4.6	DI estimated from Water into supply meters which record 90% of DI		✓			
4.7	DI estimated from Water into supply meters which record 85% of DI			✓		
4.8	Meter used are regularly recalibrated	✓	✓	✓		
4.9	Co has identified WB components likely to largest errors and is review estimation procedures			✓		
5	Overall Water Balance					
5.1	Water Balance components reconcile within 2% of DI	✓				Grade A:- All 5.1,5.3,5.6,5.7 and 5.8 to be ticked
5.2	Water Balance components reconcile within 5% of DI Adjustment made using MLE		✓			
5.3	Explicit explanation of changes to any water balance components for reconciliation adjustments is given	✓				Grade B:- As above but 5.2 instead of 5.1 and 5.3 not required to be ticked
5.4	Water Balance components have not been reconciled with DI			✓		
5.5	No reconciliation across individual components or between sum of components and DI				✓	Grade C:-if either 5.4 or 5.9 are ticked but not 5.5 or 5.10
5.6	Water into supply meters have been used and recalibrated	✓	✓			
5.7	Water balance components have been estimated separately	✓	✓	✓		Grade D:- If either 5.5 and 5.10 are ticked
5.8	90% of the distribution input volume (but not the DI itself) i.e. the component volumes .have been given a reliability band of A or B	✓	✓			
5.9	90% of the distribution input volume (but not the DI itself) i.e. the component volumes .have been given a reliability band of C or better			✓		
5.10	90% of the distribution input volume (but not the DI itself) i.e. the component volumes .have been given a reliability band of C or D				✓	

Current Classification of Water Service data ✓

Table 2.3: Example of water balance reliability grading [19]

2.3.6 Certifying OFWAT data – The role of the Reporter

Although the data from meters is graded, OFWAT operates a separate certification scheme covering all of the June Return data. Because OFWAT’s modus operandi is founded on the premise of using comparative competition to identify “Best Performers”, it requires comparable and consistent information relating to both current performance and progress.

A number of individuals, known as Reporters, supported by specialists, are employed to provide an independent opinion on reliability and accuracy.[20] Employed by the water company, they nevertheless have a primary duty of care to OFWAT, sitting independently between the two. The reporter will independently validate data and through scrutiny, assessment and test, challenge the company information before it is submitted. They nevertheless do not certify the water company’s figures. Endorsement of all reporters is administered by the UK Government National Audit Office.

2.4 FUTURE DEMAND AND WATER BALANCE MEASUREMENT

This section illustrates differing scenarios surrounding the water balance and develops the reasoning behind the need for better measurement knowledge relating to the battery EFM performance, limitations, calibration, verification and general data quality as contributing to regulatory policy.

2.4.1 Demand growth issues requiring measurement

The report [21], “Water Resources for the Future”, provides source material which sets out the relative importance of leakage as a national matter of importance. Figure 2.4 illustrates the four EA future total demand scenarios between 2010 and 2025.

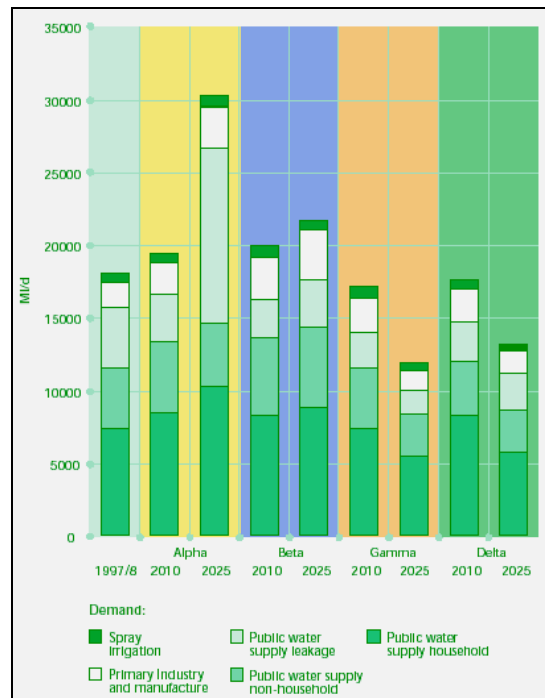


Figure 2.2: Future demand scenarios 2010 to 2025 [21]

The primary point is the dominance of the water sector, exceeding the combined value of the industrial and agricultural demand. This is followed by the projection that water leakage, in all of the four scenarios, remains high. This is matched by high aggregate household and non household supply totals.

This generic planning tool is supported by the freshwater abstraction history which, despite a reduction in the mid 1990's linked to improved leakage reduction activity, is seen to be steadily growing. The exception is fish farming.

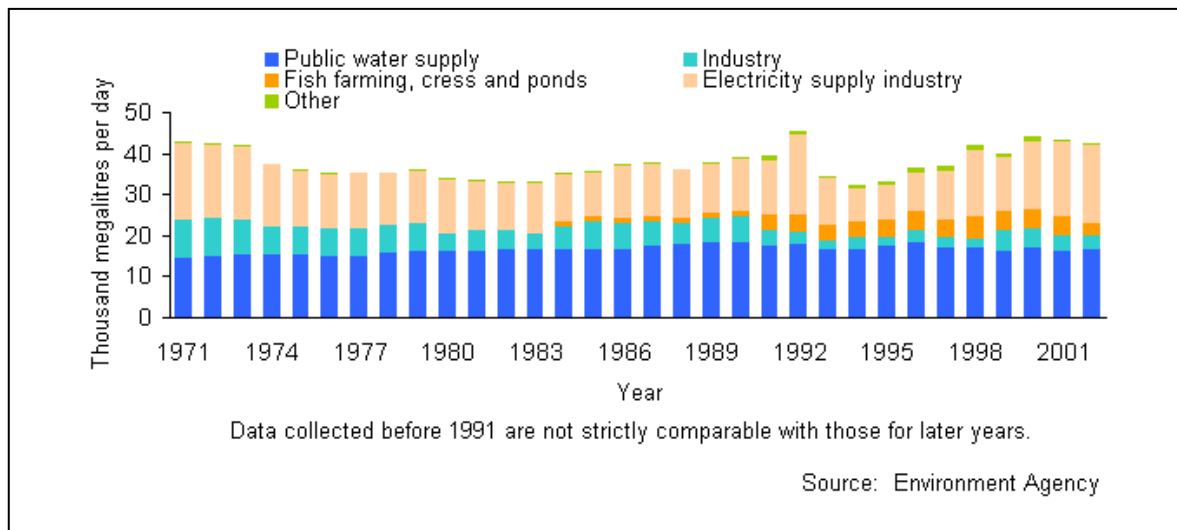


Figure 2.3: Abstractions from freshwater in England and Wales, 1971 to 2002 [21]

Corroborative evidence can be found when comparing data from the 1970's with that for the late 1990's. See Table 2.4.

	1974/5	1997/8
Public Water Supply	15155	15660
Industry Direct Abstraction	7080	3760
Spray Irrigation	78	450
Total	22313	19870
Leakage	?	3930

Table 2.4: Changes in major UK water consumption 1974-1997 [22]

The comparison shows that consumption by industry has almost halved; that irrigation has increased, but that the public water supply has remained high with leakage in 1997/8 at 19.8% of the demand. In 1974/75 no records were kept of leakage.

The recorded evidence is clear. Management of national water resources requires focus on the public water supply and, in particular, attention to the data contained within the component elements of the water balance. Such management requires accurate measurement.

2.4.2 Water into supply utilisation and metering performance demanded

Figure 2.6 illustrates the breakdown of water demand for a typical UK water plc at a period during the mid 1990's. The data shown is that for Severn Trent Water and represents actual operational information. It may be taken as broadly representative of a large UK water services provider. DI stands for Distribution Input, otherwise termed water-into-supply.

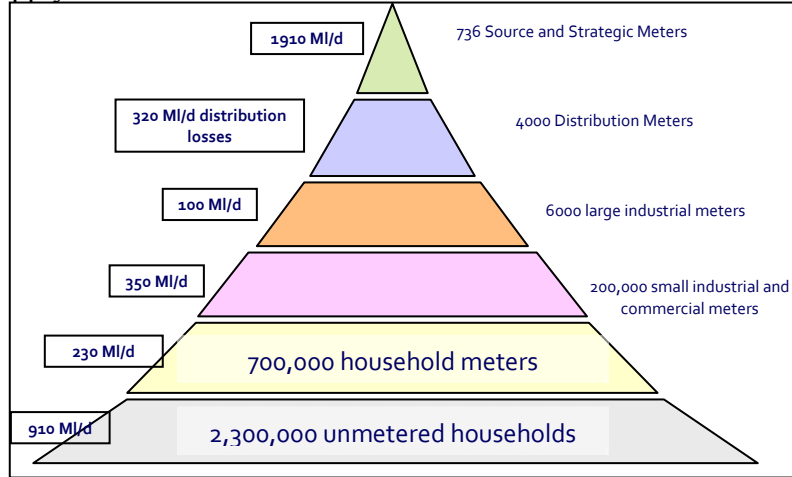


Figure 2.4: Supply system volumes and meters [23]

Broken down in order of descending component volumes, the usage is:

COMPONENT OF SUPPLY	FLOW m ³ /d	% of DI	No. of Meters
DI Input or water into supply	1910,000 (2595/meter)	100	736
Unmetered household consumption(for 2,300,000) customers	910,000	47.6	None
Small industrial and commercial meters	350,000 (1.75/meter)	18.3	200,000
Network distribution losses	320,000 (80/meter)	16.8	4000
Household metered consumption	230,000 (0.328/meter)	12.0	700,000
Large industrial consumption	100,000 (16.67/meter)	5.2	6000

Table 2.5: Supply system components and meter numbers [23]

Table 2.3 makes clear that measurement accuracy and representative population sampling are essential to developing water demand forecasts. When expressed in terms of volume passed per individual meter, the focus for metering falls on the DI input and network distribution meters. This is because these meters record the highest volumes per unit meter at 2595 m³/day and 397.5 m³/day, respectively. It is noteworthy that the distribution losses of 320,000 m³/day represents 20.1% of the 191,000 m³/day distribution input.

An examination of the unmetered household volume shows that it is particularly sensitive to the determination of per-capita volume. To address this demand component

requires that water companies derive representative data from purpose designed domestic consumption monitors (DCM) and small area monitors (SAMs)

These “data monitors” are an essential element in creating statistically meaningful information and are necessarily sensitive to the performance of the metering technology employed. For the SAM data monitor approach battery powered EFM are typically selected because of their claimed stability and accuracy over time. This contrasts to the use of mechanical meters where time related changes in accuracy can bias the results.

The point of note for the per-capita consumption component is that a small, averaged number representing an individual householder’s water use, when multiplied by a large number (that of the total number of water company customers), will return an input which is significant to the overall water balance.

This figure is, moreover, highly sensitive to the derived per unit statistic, which in turn relies upon the performance of the metering equipment. Thus metering performance, calibration and stability are key to maintaining statistics which can be reliably interpreted year-on-year, as demanded by OFWAT.

For the water company data in Table 2.5 each measured household uses 328.6 litres a day, whilst the unmetered statistic arrived at using a data monitor is 395.7. This 20% difference is very important to the relative importance of the supply contributions and is critically dependent on the representative quality of the DCM and SAM data samples.

For the SAM linked to the unmetered demand statistic, battery EFM’s are employed by the particular water company, Severn Trent, to measure aggregate demand for a discrete group of houses or a cul-de-sac. Battery EFM’s therefore contribute key flow data feeding into the water balance. Hence, knowledge of their performance, calibration, data quality and any limitations is important in building confidence in the reported aggregate demand figures submitted in the annual June return.

2.4.3 Multiple use of meter data with differing performance uncertainties

When auditing flow data it is the case that meters may have multiple uses and that data from the same instrument can appear as separate statistics. This is important because a water company may choose to allocate the uncertainty of the meter depending upon its allocated use, and not linked as one might expect to the absolute performance of the technology.

Figure 2.5 illustrates possible multiple meter use and shows how the output from a particular meter may be selected to add into either the so called “top-down” statistics, or the “bottom-up” values, when seeking to create the overall balance of flows within the particular supply and distribution system.

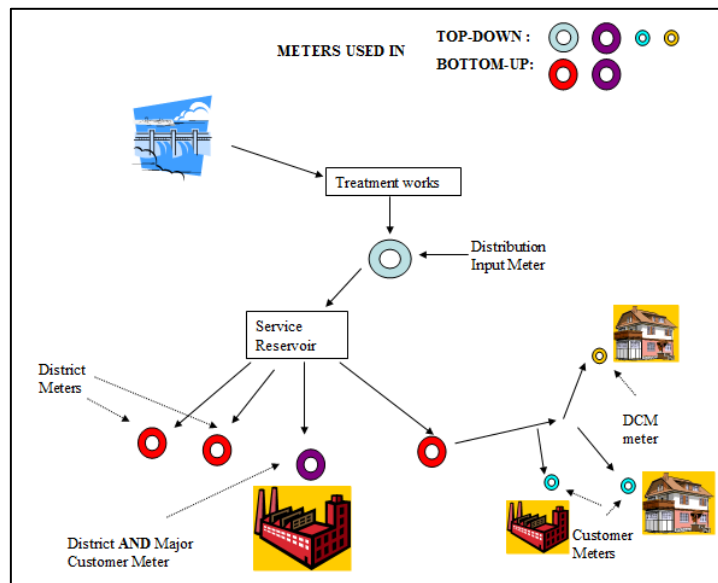


Figure 2.5: Meter locations and accounting use(s) [24]

Relevant to the work presented later in the thesis is the fact that battery EFM's are found in all three areas illustrated:

- (i) insertion EFM meters because of their role in verifying this company's 736 DI input meters;
- (ii) full bore battery EFM meters in the district/distribution measurement of leakage plus
- (iii) battery full bore meters in small area monitors helping to define per-capita consumption.

2.4.4 Water balance top-down measurement variability impact on leakage

To emphasise the importance of the metering components and the need for accurate, traceable	Reported – 2001/2	Alternative View
Households – Unmetered – consumption	867	755
– supply pipe leakage	97	141
– Metered – internal – consumption	70	70
– supply pipe leakage	10	15
– external – consumption	96	88
– supply pipe leakage	3	11
Total household water delivered	1143	1080
Non-household – consumption	467	467
– supply pipe leakage	5	5
Other water delivered	30	30
Distribution system leakage	225	288
Total into supply	1870	1960
Total leakage	340 (18%)	460 (24%)

Table 2.6: Leakage analysis sensitivity [24]

In Table 2.6 leakage has been first calculated with the company's own internal data,[23] arriving at a figure of 18% of DI input. The second calculation makes recourse to OFWAT's published data for the water industry as a whole [25] which shows a wide spread in the data relating to household consumption and supply pipe leakage.

The "alternative" view of the same company's leakage, shown in Table 2.6, was thus derived using revised figures typical of the industry not the company. This alternative, shown in the table, has changed the total leakage significantly, elevating it to 24%, from the 18% originally claimed. And because the industry wide values are derived from estimates claimed to be representative of typical household consumption, it can be argued that the alternative view has equal validity with the original.

A technique to minimise the spread in results when undertaking and reconciling the top-down analysis, centred on the use of uncertainty bands, is dealt with in chapter 9 where a more mathematical and rigorous approach to the water balance, using maximum likelihood estimation (MLE) [26] is addressed.

Two points emerge from this illustration:

1. that, in the absence of measured data of known provenance, the calculation and uncertainty of the water balance and of leakage in particular, is capable of significant alteration arising from the use of estimated flow values
2. that to be able to calculate leakage consistently, accurate knowledge of meter performance is essential when meter measurements are used in reconciling the water balance.

2.5 DATA MONITORS AND VERIFICATION QUALITY ASSURANCE FOR WATER BALANCE INPUTS

2.5.1 The role of data monitors and role of battery EFM's

It is a feature of water supply arrangements within the UK that residential supplies are unmetered in the majority of cases. This creates a difficulty in assessing the true value of the un-measured household consumption component within the water balance. To resolve this problem domestic consumption monitors (DCM's) and small area monitors (SAM's) have been created.

In the case of a DCM the water company begins by creating a profile of the households making up the population within its area of supply. This profile can be very sophisticated, reflecting the make-up of family groupings within society. As such it is subject to change over time as patterns of behaviour alter e.g. the rise in the number of smaller households due to increases in the frequency of one parent families; the rise in popularity of dishwashers; etc

Once the profile of the customer base is understood, a statistically representative number of households are nominated, often around 2000. Individual households are then chosen such that, overall, they reflect the general consumer profile of that water company. Each of these households is then fitted with a traceable meter, often individually calibrated and flow data collected over a period of years. In the case of Severn Trent Water their DCM was created in 1985 and has tracked consumption over

25 years. During this time the meters have been replaced twice and the profile of homes monitored updated regularly on a five year basis. [27]

Alongside the DCM a second data monitor has been developed, the SAM. This monitor complements the DCM and is engineered to measure the demand of a group of properties, representatively between 30 and 50 in number. Physically a SAM will typically consist of a single meter feeding a cul-de-sac in which the houses are set. Unlike the DCM, the SAM measures not only the demand from the individual households but the leakage associated with the 100mm or 150mm network pipework feeding the cul-de-sac, plus the leakage of the individual supply pipes from the network pipe to each house.

Statistically, data from a SAM is often correlated with the type of network pipe material – cast iron; cement lined ductile; MDPE; steel; etc in order that the average SAM derived household demand can be mapped against the pipework profile across the water company.

By combining data from the DCM and SAM installations not only can values be derived for average un-measured household consumption but also the levels of leakage associated with the network pipes supplying those households, can be derived.

In respect of the technology deployed, for DCM applications 15mm semi-positive displacement mechanical meters are used, whilst for the SAM installations, buried battery EFM's are the preferred choice.

The performance, limitations, data quality and long term stability of these meters is therefore directly linked to the quality of the water balance.

2.5.2 History of meter verification technical procedures

As outlined earlier, following the establishment of the NRA, later part of the EA, metering had been identified as a key issue in regard to abstraction licensing. The initial Severn Trent Water meter verification programme, established by the NRA[28] was expanded to other water companies and expanded to include meters measuring water-into-supply volumes. These were regulated by OFWAT. However, neither OFWAT nor the NRA/EA had created verification technical guidelines and the initiative lay with the individual water companies to progress flow measurement and data quality issues.

The development by NEL in 2002 of a series of guidelines for auditing of water flow metering systems [29], created technical clarity but was not formally linked to regulatory control. Because of this, regulatory policy relating to the verification of large water-into-supply (WISPY) meters remained generally unchanged despite the publication of an excellent series of documents by NEL.

To add to the weakness in the regulatory approach there was a lack of consistent company to company procedures, plus a lack of accurate, traceable field data needed to frame and implement the necessary guidelines. Pragmatically, it was the case that continuation of the un-standardised situation did not disadvantage the majority of water companies, reducing the incentive to innovate.

2.5.3 Verification methods and preferred choices

The range of methods open to water plc's to satisfy the original NRA requirements for verifying the major water-into-supply meters is shown in table 2.7.

METER VERIFICATION OPTIONS	COMMENTS	ADVANTAGES/DISADVANTAGES
Reservoir Drop Test	Historically, the original option used by companies using own reservoirs to provide check volume/flow	Requires a great deal of knowledge about the volume v stage relationship of the reservoir. Operationally very difficult to manage whilst running a real-time meter verification. Only useful for gross ± 15 -20% checks at best
Check or Transfer Standard Meter	Can work in smaller distribution zone applications. Requires critical checks to be made on the master meter at frequent intervals. Not practical on meters larger than 150mm, i.e. WISPY meters	Can deliver good accuracy but is fraught with problems regarding isolation of the meter under test. Tried and generally abandoned by water companies (including the author). Recent (post 1998) operational and hygiene requirements make this approach unusable at most locations.
Thermodynamic Method applied to Pumped Systems	Needs a decent differential head across pump of the order of 10 bar. Limited by location but a powerful tool when done properly.	Success is directly linked to attention to detail in methodology. Can provide sub 1% verification of flows but often is used where there are no installed meters.
Clamp-on Ultrasonic Metering	Non intrusive method which brings advantages of near universal application and disadvantages of lack of knowledge of flow profile and flow hydraulic conditions.	Much improved in the last 10 years. Practical advantages often confused with deliverable performance. Needs pipe condition and make-up to be known, which are often clearly unknown to the test operator.
Tracer Techniques	Wonderful standards but impractical when attempting to apply to 'live' distribution networks required to meet high water quality standards	Possible on bulk untreated flows. Successful Process Industry use cannot be translated to the Water Industry due to inapplicability of radio-active tracers or difficulties with water quality.
Insertion Techniques	Predicted on velocity measuring devices including pitot tubes (differential pressure), turbine meters and electromagnetic probes.	Long history with good track record delivering reasonable accuracy of between 6-10% where hydraulics permit. Significant advantage is that measurement of raw velocity can provide feedback on in-pipe hydraulic conditions. Demands investment in tapping points and can be relatively slow.

Table 2.7: Summary of verification methods

Table 2.7 excludes static verification instruments, SVIs, because the technology had not been developed at that time. With minor exceptions, where no practical alternatives existed, three verification techniques were adopted by the water plc's from this list of possible approaches, namely:

- a) insertion based methods applying probes both as fixed meters and using traversing methods to determine the velocity profile;
- b) the thermodynamic pump efficiency/ flow method and
- c) clamp-on time-of-flight ultrasonic meters.

Decisions pertaining to the choice of each method related primarily to site-specific applications suitability, decided by the WISPY meter location, size and hydraulics.

Taking Severn Trent Water as an example, it chose to use:

- the thermodynamic technique for large pipework where no meter was in place due to poor hydraulics and/or lack of space; applied to less than 5% of WISPY meters;
- the clamp-on technique for pipe sizes of 150mm, or less, where use of proprietary probes were stated to be inappropriate[30]; applied to about 10% of WISPY meters;
- insertion profiling; applied to the majority, 85% of WISPY meters.

To contrast the different advantages and disadvantages of the insertion probe and clamp-on methods refer to Table 2.8.

In addition to the above methods, static verification instruments, SVIs, have recently been adopted by a number of water companies. These instruments are not explicitly examined within this thesis but further details may be found in references [31] and [32].

Feature	Insertion Probe		Clamp on ultrasonic meters	
	Advantages	Disadvantages	Advantages	Disadvantages
Measurement signal		Provides only the local point velocity measurement where the probe is located (radially) within the pipe	This integrates the flow velocity across a pipe and calculates a total flowrate	
Velocity profile	This can be used to determine the velocity profile across a pipe (eg. 11 traverse points across a diameter)			Cannot be used for determining the shape of a pipe's velocity profile
Total flowrate	Once the velocity profile is known and it has been ascertained that it is stable, the probe can be positioned on either the centre-line or the 1/8d position and total flow can then be calculated and the correction applied. Signal is continuous.	Determining the velocity profile is time consuming (1/2 to 3/4 hr) and needs to be determined at more than one flowrate to demonstrate flow profile stability	This device measures velocity across a chord length of the pipe or in 'Z' path configuration. Calculates total flow. It has a continuous output signal. Once mounted in position readings are updated continuously. Once set up, easy to use.	
Inlet piping configuration	This can be used with adverse piping configurations and asymmetrical velocity profiles provided the relative shape of the velocity profile does not change with flowrate			Configured as a single path meter must be used with fully-developed velocity profile. Multi-path set-up is less affected by asymmetric velocity profiles. Single path more sensitive
Sensor location		This is an 'intrusive' method. Suitable traverse bosses have to be located on the pipe wall. At least one boss, preferably two are required, 90 degrees apart.	This is a non-invasive method. The sensors are clamped onto the outside of the pipe wall. Access required to the pipe circumference	If used for long periods at one location, the coupling 'path' tends to slowly deteriorate with time (weeks/months) causing a fall-off in signal performance
External and internal Wall surface finish	Unaffected by external wall surface finish.	Probe readings near the pipe wall can be affected by the internal surface finish. A corrugated pipe-wall can have a more adverse effect.		Meter performance is sensitive to the quality of external and internal surface finish; internal lines, wall coatings and wall corrosion. Essential that sensors make good contact with external pipe wall. Sensitive to pipe seam welds.
Wall thickness	Unaffected by wall thickness			Pipe wall thickness, lining and all material specifications must be known.

Table 2.8: Comparison of insertion v clamp-on verification techniques

2.5.4 Aspects of (battery) insertion metering and meter verification

Although the water industry had historically used a variety of insertion methods to measure the flow into supply and across networks, within the last 25 years the technology has advanced. Whilst the underlying principles have remained i.e. the determination of the bulk flow from the measurement and integration of localised pipe velocity, the velocity measurement technology has evolved. Former methods, relying on differential pressure or mechanical insertion turbines, have within the water industry been replaced by sensing of the flow using electromagnetic, velocity based techniques.

As the name suggests, insertion metering consists of an invasive method of determining flow, effected by introducing a probe into the pipeline. The method is engineered by the drilling and tapping of the pipe in question. To do this a boss, attached to a collar surrounding the pipe is fixed in position. The boss and underlying pipe wall are then drilled to provide a tapped entry into the pipe.

Unlike laboratory installations where the pipe is drilled directly, water industry applications include the height of the collar and the isolating gate valve. This fixes the probe support point several hundred millimetres above the pipe crown, effectively extending the insertion distance. This extended cantilevering of the probe changes the natural vibration frequency of the probe assembly, limiting the maximum flow velocity at which the probe can be safely or accurately operated. Chapter 6 considers this limitation.

Current EFM probes are based upon diametrically opposed sensing electrodes with the field coil system embedded within a synthetic material engineered to the same dimensions as the insertion rod. Other designs have been engineered, based on an annulus appended to the end of the insertion rod. This “through the hole” design mimicked, in a solid state version, the traditional insertion turbine meter and was evaluated with mixed results by the NEL Insertion Flowmetering Consortium [33].



Figure 2.6: Two designs of insertion electromagnetic probes

Others designs use generalised hydraulic theory, positioning a button type EFM sensor close to the pipe wall. However, the so called ‘stick meter’ approach shown in figure 2.6 represents the most widely adopted design.

Deployment of insertion EFM probes as fixed meters has become common, replacing older technologies such as the averaging pitot designs which were widespread in the water industry in the 1970 and early 1980's,[34] but which suffered from limited turndown - maximum to minimum flow velocity. Table 2.9 provides a comparison of the advantages and disadvantages of the different insertion technology solutions.

Type	Differential Pressure	Mechanical Turbine	Electro-magnetic	Boundary Layer
No moving parts	×	×	✓	✓
Maintenance required	×	✓	×	×
Linear / Square law	✓	×	×	×
Affected by hydraulic flow profile	✓	✓	✓	✓

Table 2.9: Comparison of the attributes of different probes technologies

However, calibration traceability of the EFM probe flow data cannot be directly related to physical, dimensional and fluid property laws, as remains the case for the pitot design. In the EFM probe designs the sensed velocity is itself part of a traceable chain linked to the manufacturer's calibration.

2.5.5 Insertion Probe Sources of Uncertainty and Limitations

In contrast to use of EFM probes as fixed meters, their application to meter verification relies on adoption of developed methods of integrating point velocities to arrive at the bulk flow. Published standards, notably BS1042 [35] rely on establishing the velocity profile at the point of verification, then using the mean or centre line value to compare, over time, the probe flow with that of the meter under test. Such operation introduces a range of uncertainties to the derived probe-flow.

Table 2.10 generically represents the principle sources of uncertainty associated with deployment of an EFM insertion probe meter in a profiling and verification role.

Source of Uncertainty
Sensor/transmitter calibration
Calibration and its application validity
Transduction of the flow velocity - excitation mode(s)
Flow induced vibrations
Characterisation of the probe blockage factor
Physical and surface effects on probe head
Alignment with flow direction
Calculation of profile factor
Positioning within pipe
Data sampling regime
Effects of non ideal flow
Conductivity and temperature influence factors
Type of flow regime
Lack of local velocity and profile intelligence
Operator inconsistency in implementing profiling technique

Table 2.10: Sources of uncertainty pertaining to insertion probe use

To rigorously incorporate data into the calculation of the water balance derived from EFM probes meters and/or from meters verified using probes, all of the performance aspects listed in Table 2.10 ought to be addressed.

Application of a profiling methodology, compliant with the relevant standard, is still subject under practical installation conditions to additional variability caused by the actions of individual personnel. This source of predominantly operator centred error has historically been ignored as it is very difficult to manage; primarily because of lack of measurement precision within the flow recording regime.

Such imprecision in the detail and the volume of data leads to a dearth of information on which meaningful measures of performance can be based. It can be minimised through the application of quality systems principles to the insertion probe verification process and by improving data recording.

Chapters 5 and 6 expand on these technical and data quality issues, examining probe performance, calibration, traceability and data quality.

2.6 REVIEW SUMMARY AND FOCUS FOR BATTERY EFM EXAMINATION

- Examination of the future demand scenarios in the UK has confirmed that accurate measurement of the demand components comprising the public water supply (PWS) usage can best lead to improved utilisation of the available natural resources across the water cycle.
- Accurate measurement of flow is central to managing the component parts of the PWS water balance. This requires knowledge of the performance and

limitations of different meter types when installed in representative network locations. These data are presently lacking for the battery powered EFM meters which have been introduced over the last 5 -10 years.

- Leakage determination is central both to achieving PWS water balances and to directing efficient network operations. One component in calculating leakage relies upon generating representative values for the unmeasured water balance components, (matched to population estimates), through the use of data monitors.
- Such data monitors may use buried, battery EFM's. However, long term performance of this type of meter has not been researched and work is required to assess their calibration stability. This research is important in order to assure the integrity of the data monitor results, affecting in turn the accuracy of the estimates for unmeasured demand within the water balance.
- The task of assuring and improving the quality of data derived from a variety of verification methods (for the key water-into-supply meters comprising the largest component feeding the water balance), is central to allocating objective values of uncertainty to these meters.
- Consistency and traceability on a year to year basis when reporting data from individual metering assets is essential to the determination of trends in overall performance. Within this quality assurance process weaknesses exist in both the traceability of the methods being employed and through variability introduced by human factors in the chosen verification scheme(s). These weaknesses should be addressed.
- In light of the above and working within the limitations of the thesis scope, it was therefore proposed to include the examination of one meter verification method in detail. The method chosen was that of determining the bulk flow from velocity profiling. It was identified as a suitable case for study because the battery EFM probes used in operating the method had been introduced using guidelines framed only by the manufacturer. This had created a lack of independent information on which to build confidence in the verification technique and to independently demonstrate traceability of the test results.
- The examination aimed, in detail (a) to examine traceability and uncertainty and (b) to identify process improvements related to human factors influences inherent when applying the technique.
- Summarised, the thesis will examine the performance and limitations of both the battery full EFM meter and the battery EFM insertion probe variant, addressing the calibration, verification, stability and data quality aspects of the battery EFM technology where it impacts on regulatory policy.

3 BASICS AND BACKGROUND TO BATTERY ELECTROMAGNETIC METERING DEVELOPMENT

OBJECTIVE

The aim of this chapter is to set the scene for the work undertaken, outlining the history and evolution of the battery EFM meter within the UK water industry, the main functional features of the design tested and the general areas of investigation which form the basis for the thesis research.

3.1 ELECTROMAGNETIC METER BASICS

3.1.1 Principle of Operation

The self taught researcher Michael Faraday first recognised the possibility of inducing voltages in liquids moving through a magnetic field as far ago as 1832. However, it was almost a hundred years later that Williams(1930) [36], reported the first flowmeter device based on this principle in a paper to the Royal Society.

The construction of a representative modern flowmeter is shown in figure 3.1 and has the essentials required of any electromagnetic meter. These are (1) a source of magnetic field (2) a flow tube which is lined and insulated to prevent shorting of the induced voltages and (3) a pair of electrodes to sense the flow induced voltage.

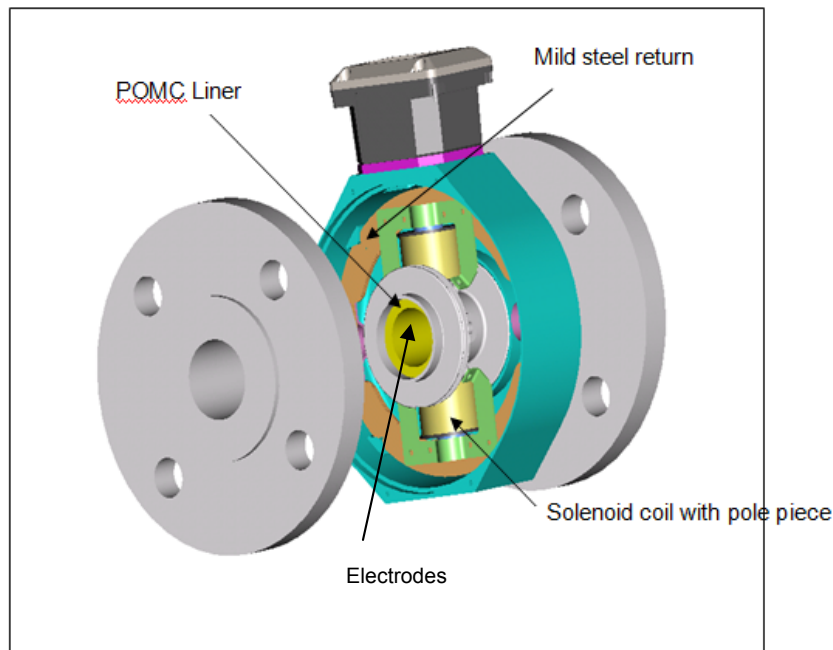


Figure 3.1: 3D cut away of modern electromagnetic flowmeter sensor

The voltage between the electrodes is given by:

$$E = SBDu \quad (\text{Volts}) \quad (3-1)$$

Where S=the individual flowmeter sensitivity

B = mean, or representative, magnetic flux density

D = diameter of pipe u = mean velocity of the fluid

Underlying this basic equation relating voltage to fluid velocity are two assumptions: the first is that the magnetic field is uniform, the second that the velocity profile of the fluid passing through the meter is axi-symmetric.

3.1.2 Sensor Design and Weight Function

The major advance in overcoming the limitations of the basic theory was proposed by Shercliff in his 1962 book[37] introducing the idea of a weight function. This function may be represented on a diagrammatic cross-section of the meter by contours, as illustrated in figure 3.2. These indicate the relative weighting which a component of flow passing through that point would receive, when integrated to yield the true signal.

Figure 3.2 shows such a weight function for a meter with point electrodes and a uniform field.

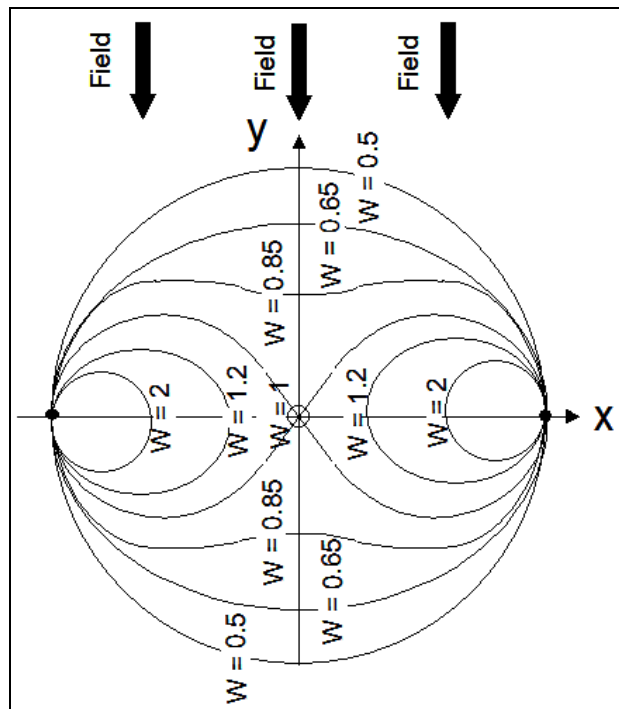


Figure 3.2: Weight function for a point electrode flowmeter with a uniform magnetic field

Work by Bevir[38] and then Hemp[39] in the 1970's extended the Shercliff approach. Development of numerical calculation methods has enabled the realisation of the theory and calculation of weight function and now forms the basis of the electromagnetic meters designers' toolkit. Practically the outcome is that improvements in knowledge of the field have created successively more compact sensors with non-ideal and non-uniform field distributions to generate linear outputs when driven with the relevant transmitter.

An alternative approach, which was pursued, was that described by Hemp and Sanderson[40]. This increased the size of the electrodes and improved the theoretical performance by decreasing the sensitivity of the weight function, increasing capacitance

and lowering noise. However, one of the reasons for not developing this approach was the difficulty in manufacturing the shaped electrodes.

3.1.3 Transmitter Aspects

The first large scale production EFM meter designs operated with a.c. driven fields. However, their performance was generally poor, partly because of limitations in the then available electronic designs but principally because of drift and transformer induced interference signals which resulted in unreliable measurement of the flow. These practical failings forced the adoption of a variety of d.c. driven designs which subsequently, with the exception of high speed response meters, have become standard for the majority of EFM meters and for all those used within the global water industry for the measurement of water network flows. Switched d.c. EFM metering, described by Hafner[41] at the 1985 NEL conference, delivers improved zero point stability, reduces noise and when combined with increased frequency of excitation and modern digital filtering meets many of the original ideal performance criteria demanded by users.

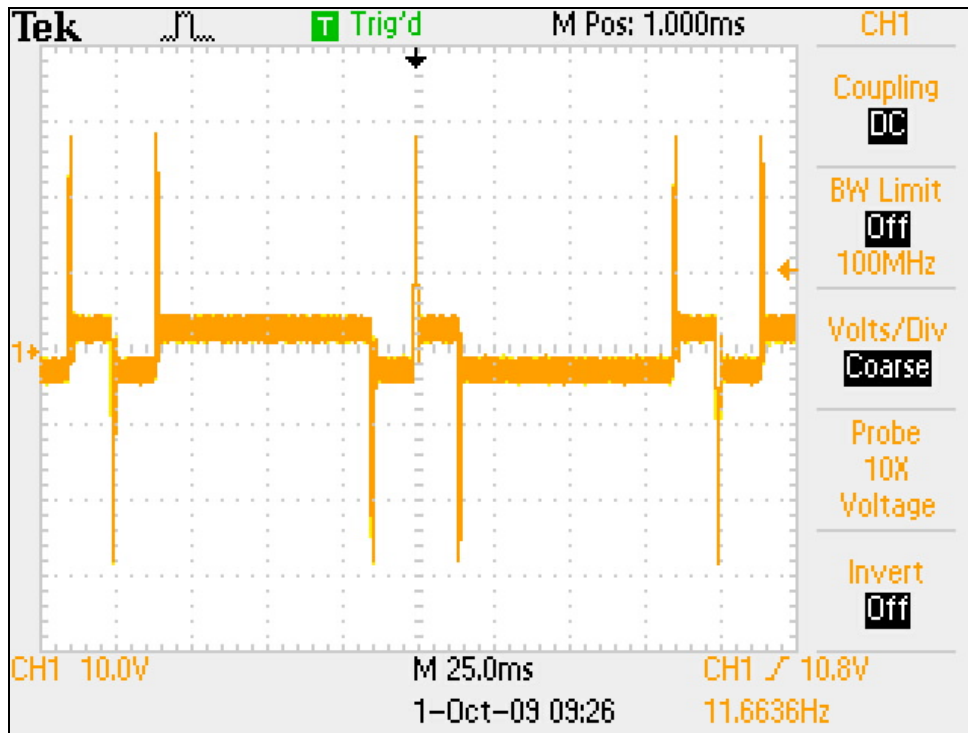


Figure 3.3: Illustration of a commercial mains powered bi-polar, switched dc field drive (after Hafner); ABB's mains powered EFM, measured at Hams Hall laboratory

Since that time, the advance of electronics has refined and improved performance, as reported by Herzog[42] in the 'Flow Measurement for Utilities' conference in Amsterdam. However, subsequent improvements have been incremental and technology based, rather than representing fundamental advances.

3.2 DEVELOPMENT OF THE BATTERY EFM METER

The creation of an industrial design of battery powered water flowmeter can be directly traced to an industrial, water industry technology initiative from the Instrumentation, Control and Automation (ICA) unit of the Severn Trent Water Authority (STWA). In 1985, this group, managed by Stuart Walker, issued a three page specification describing the functional performance and outputs needed for a non-moving parts water distribution flowmeter. The specification was sent to all major international and national manufacturers, drawing a wide variety of responses. The majority view from manufacturers was that the concept was novel but impracticable. Nevertheless, the Kent industrial measurements division of Kent Meters, a UK organisation, accorded it a more enthusiastic reception and entered into a joint development agreement based on the broad specification given in table 3.1

General	
	Application within water distribution system operating conditions.
	Equal performance to standard mechanical meter - Woltmann type.
	+/-5% of reading Q_{min} to Q_t ; +/-2% Q_t to Q_{max} .
Sensor	
	Size range 50mm to 150mm
	Velocity range 0.05m/sec to 5m/sec i.e a turndown ratio of 100:1
	Designed to allow burying e.g.the flow sensor is bolted into the existing pipework and the surrounding excavation back filled.
Transmitter	
	1 year battery life under standard operation.
	15 minute measurement and output of flowrate.
	Standard transmitter capable of being programmed to suit sensor.
	On demand visual display of flowrate.
	Programmable pulse output.
	Capable of interfacing to Spectrascan datalogger.
	Plug and socket design to connect to sensor, logger and battery.
	IP68 housing capable of being installed in flooded chamber locations.

Table 3.1 : Basis of the original battery EFM meter development specification.

Alongside the novel battery powering of the EFM meter was the equally radical demand that the sensor be capable of being buried. This requirement stemmed from the underlying economics of the EFM meter which, in order to be able to compete with the existing mechanical meters, needed to avoid the high cost of constructing a chamber to house the sensor. The end result of the development contract from STWA was the production of 80 VKB battery units[43] by 1987, thus starting a new chapter in the application of EFM metering within the water industry. Prior to that time water industry EFM's had been restricted to using mains powered instruments, limiting their use to small numbers principally used as works output meters. After 1987 battery EFM's began, albeit slowly, to penetrate the water distribution meter market where the numbers of installations were counted in thousands rather than in tens of units.

3.3 BATTERY DESIGN EVOLUTION AND GAPS IN KNOWLEDGE

3.3.1 History and Evolution of Battery Designs

From 1985/7 to around 2003, the evolution of battery metering followed the product upgrades of the original manufacturer with further changes to the sensor construction and revised transmitter housing. The performance specification remained unchanged. The housing modifications were introduced to address the poor reliability record of the transmitter, where water ingress was a major cause of failure. However, within this apparently seamless progression, the underlying method of battery operation and signal processing changed substantially. In 1998, the manufacturer launched a model utilising a radically revised design of transmitter which, unlike the earlier device which sampled at 15-minute intervals, operated at much lower power but at 15-second intervals, integrating the results to produce an averaged 15 minute output.

Unlike the two previous, evolutionary, designs, ABB's unit was fully digital and incorporated a pre-amp circuit physically located within the sensor housing. This novel design feature both eliminated earlier application limitations associated with loss of signal with cable length and allowed the direct exchange of transmitters. The sensor design was also radically changed, featuring a reduced area cross section. Details are given in the NEL Flow Measurement 2001 Conference by Thomas et al[44]. It is this design which has been the subject of examination, representing as it does the new generation of battery EFM meters which combine a fully digital sampling transmitter with a sensor designed to optimise the turndown ratio and hydraulic performance.

3.3.2 Details of ABB's battery EFM meter evaluated in the thesis

The transmitter designs for the battery EFM are shown in figure 3.4. Although physically different, the internal electronics board and component count are the same, with the different casings representing differing production, not functional instruments.



Figure 3.4 Battery EFM showing the two styles of transmitter housing

The key feature of the battery design lies in its fully configurable nature, with all active elements of the electromagnetic meter being settable. The configuration is built on 412 individual, programmable parameters accessible through an RS232 communications port; with functional security administered by allowing different levels of access to operators through a structured, coded password system.

Variable Identity	Variable Description	Read Access	Write Access	Location Tx/Sensor	Enumeration Table No.
>0=	Software version No	0	N		
>1=	Unique sensor serial number	0	7	S	
>2=	Flow sensor software rev	0	7	S	
>3=	Flow sensor hardware rev	0	7	S	
>4=	Flow sensor preamp gain	0	7	S	
>5=	Empty pipe cal span	0	4	S	
>6=	Simulator cal	0	7	S	
>7=	Flow sensor is reverse wired	0	6	S	
>8=	Flow sensor is a probe	0	6	S	Table8E
>9=	Flow sensor nominal bore (full bore only) (mm)	0	6	S	
>10=	Flow sensor Span	0	6	S	
>11=	Flow sensor zero correction (Mains Mode) (0.01mm/s)	0	6	S	
>12=	Flow sensor settling time (battery mode) (0.1ms)	0	6	S	
>13=	Flow sensor span trim (battery mode) (%)	0	6	S	
>14=	Enable empty pipe alarm	0	2	S	Table6
>101=	Amodem version	0	N	T	
>102=	Flowmeter directional mode	0	4	S	Table16
>103=	Analog1OPFn	0	3	S	Table17
>104=	Zero output for analog1	0	3	S	

Table 3.2: Example of parameter allocation between transmitter and sensor

Table 3.2 lists an illustrative sample of the meter's software parameters showing:

1. the software variable identity;
2. the description of that particular software parameter's individual function;
3. the security level required to be able to view (read) the parameter: 0 is freely viewable, parameters with level 5 and above are restricted to authorised personnel;
4. the security level to change (write) that same parameter: level 4 and below give public access, level 5 and above give factory access only;
5. where, physically, the particular software setting is held: S is when it is located in the sensor and T indicates it is in the transmitter; and
6. the reference of the linked enumeration table which codes for specific functionality.

The enumeration table refers to a separate list providing all of the possible programmable values which can be associated with the particular parameter.

Table6	0=No	1=Yes		
Table7	0=NO	1=NC		
Table8A	0=DegC	1=DegF		
Table8B	0=Off	1=On		
Table8C	0=Disabled	1=Enabled		
Table8D	0=Abs	1=Gauge		
Table8E	0=Full Bore	1=Probe		
Table9	0=0	1=dial	2=1	3=1+dial
Table10	0=Off	1=Rst	2=run	3=Rst-run
Table11	0=DDMMYY Y	1=YYMMDD	2=MMDDYY	
Table12	0=std	1=life	2=perf	
Table13	0=256	1=512	2=1k	3=2k
Table14	0=Any	1=linc	2=Dec	
Table15A	0=Off	1=On	2=Pulse Fwd	3=Pulse F+R
Table15B	0=Off	1=On	2=Pulse Rev	3=Fwd
Table15C	0=Off	1=On	2=AI-NO	3=AI-NC
Table16	0=Normal	1=Backwards	2=Fwd only	3=Rev only
Table17	0=none	1=Q	2=P	

Table 3.3: Example of programmability of individual meter functions

Table 3.3 shows a sample taken from the complete set of enumeration tables where it can be seen how a single parameter may be variously interpreted according to the programmed value chosen. e.g. parameter 102, the flowmeter directional mode can be variously set to be in one of four states as given in enumeration table 16. Setting to 0 sets the meter to process all flow signals whatever the direction of the flow; setting to 1 reverses the installed meter direction; setting to 2 restricts the meter to registering only forward flow and finally, setting to 3 restricts the meter to registering only reverse flows.

As a general feature the majority of programmed parameters are held within a non volatile EEPROM memory located within the sensor housing. However, a few are held within the transmitter only, of which the most notable are those associated with the optional pressure transducer. Locating the bulk of operational parameters within the sensor has significant operational advantages when commissioning meters, or when replacing faulty transmitter units. This is because it avoids having to uniquely match a particular sensor with a specific transmitter. However, because operationally not all meters will have the same output requirements this feature generally causes the user to have to reprogram the meter at some point during its installed life e.g. when fitting a datalogger. The consequences of this may, if incorrectly done, affect both the value and quality of the battery meter's recorded data. Thus, another of the research aims, reported within Chapter 7 was to examine an installed base of battery EFM meters in order to assess and quantify the importance of such user interaction.

Description	Value	Units	Description	Value	Units
Software Version	V1.02		Coil Current	0.0567753	
Flow Sensor ID	0.01		Flow Preamp Gain	3.00081	
Flow Sensor (Batt)	0.63569		Empty Pipe Zero	0.01	
Flow Sensor Contract No	V/20017/3/3		Flow Sensor Bore	80	
Pulse Output Units	1l		Flow Sensor Zero Low Current	-10	
Pulse per Pulse Output Units	1		Flow Sensor Setting Time Constant	350	
Calibrated Velocity	0		User Flow Sensor Cal	1	
Raw Tx Velocity	0.00662782		User Flow Sensor Zero	0	
Left Electrode Resistance	4.69407		Flow Cut Off Low	9	
Right Electrode Resistance	4.75766		Flow Sensor B-H Coef B	0	
Sig A Voltage	0.281183		Flow Sensor B-H Coef A	0	
Sig B Voltage	0.269771		Display Timeout	0	
Direction	0 No		Error	512	

Table 3.4 : Example of functional parameters accessible digitally through RS232

Table 3.4 provides an example of parameters which, unlike a conventional meter, can be easily and rapidly accessed through the battery EFM transmitter's communications port. Variables shown range from the firmware/software version; the contract details; raw velocity readings in m/sec; electrode resistance; coil current; flow cut-off (in mm/second); B-H curve correction factors; and an error code parameter -512 in the above example, indicating a fault with the measured signal. The point of note is that the battery EFM design allows the user, through access to the complete set-up parameter list, not only to configure the operation of the meter but also to access real-time data and status information.

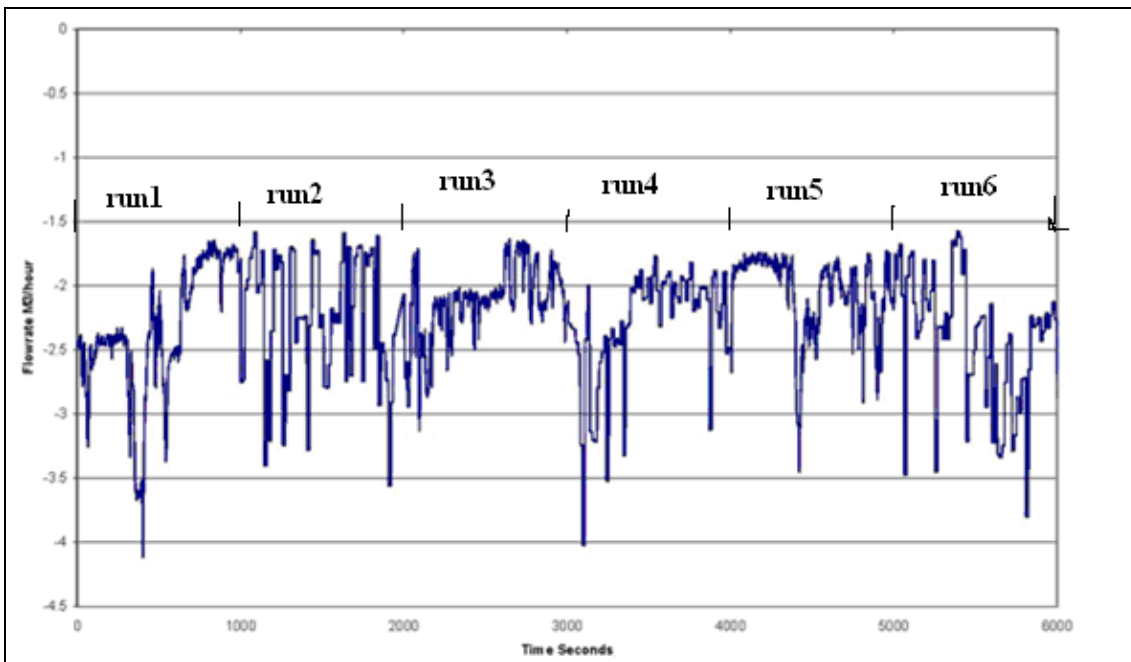


Figure 3.5: Logged battery EFM flow: as measured with alternating periods of differing excitation refresh rate

Figure 3.5 illustrates this ability to examine the meter performance in detail and under differing operational modes.

The graph illustrates the output from a battery unit logged in real time over six continuous runs. For the first, third and fifth runs the meter is operating with one second repetition of the field excitation; for the second, fourth and last runs the same meter is operated in the factory set, standard, fifteen second intermittent excitation and reading mode. As can be seen the quality of the data differs significantly. The underlying reasons are described in the chapter on the long term stability of the battery meter. However, the illustration is to demonstrate the range of functional change which may, depending upon localised conditions, affect battery EFM performance and data quality.

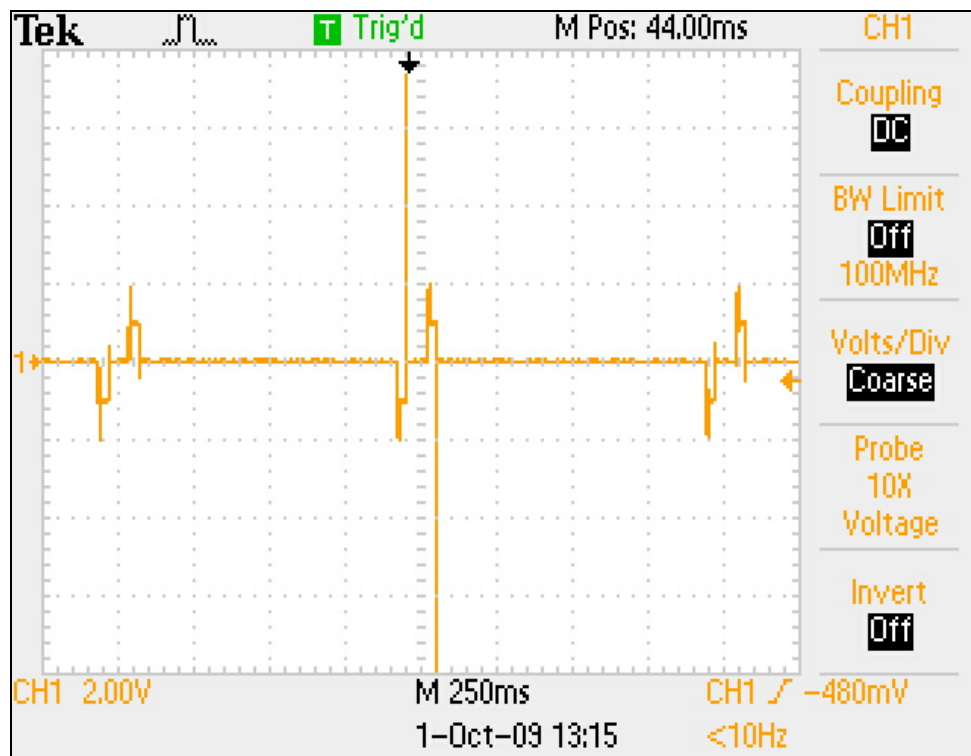


Figure 3.6: Battery EFM drive - 1 second back-to-back mode: >321=0;>343=1;158=1

Figure 3.6 illustrates in more detail the coil drive of the battery EFM meter. As shown, the unit has been programmed to operate with a one second repetition rate, representing the maximum frequency of operation.



Figure 3.7: 1000mm battery EFM insertion probe assembly

Figure 3.7 shows the insertion probe variant of the battery EFM design. As described earlier, the programmable nature of the transmitter allows commonality of the electronics. Variables such as the probe coil resistance; B-H curve correction; coil current; hydraulic correction values and the size of the pipe into which the probe is installed are all settable. As with the full bore battery EFM meter, access to the raw and processed measurements is available, making possible the ability to examine the raw electrode voltages as well as the final computed flow rate.



Figure 3.8: Detail of insertion probe tip assembly

Figure 3.8 provides a close up of the probe tip showing one of the electrodes. Note the contoured end to this new probe. When new this rounding helps to lower the level of noise observed on the flow signal, measured at the electrodes, which occurs on probes with damaged tips.

In summary, the inherent digital design of ABB's battery EFM meter provides a level of functional flexibility not previously seen in utility operated water flow meters. Whilst offering the individual user many advantages, through access to both raw and diagnostic data, the overall measuring scheme is open to mis-application because of the wide range of parameters which may be (incorrectly) altered.

In regard to setting of the underlying mode of operation, principally the repetition period for field excitation, this parameter has been set by the manufacturer at fifteen seconds in order to provide a long operational life. However, as to whether the manufacturer's claimed performance is achieved, both initially and in the longer term, with this standard set-up is one of several questions which the research aimed to answer.

3.4 THE FOCUS OF RESEARCH

In order to examine identified gaps in knowledge five areas of work were targeted. They are listed and described below.

3.4.1 Full bore battery EFM calibration and performance (Chapter 4)

The release of ABB's digital battery EFM meter was accompanied by a significant change in claimed performance for this technology. Marketed as a mechanical meter replacement, the battery EFM specification was published as meeting ISO 4064, class C. This placed it at an advantage to the majority of mechanical meters used in water distribution measurement because of the extended capability to measure at lower flowrates. However, no published independent results were available. In addition, standard water industry distribution meter installations typically feature meter use on pipework bypass arrangements where the possibility of swirl and skew flow can be present.

There therefore existed a clear requirement to explore the calibration and performance of the battery EFM meter, using the published ISO 4064 standard as reference.

3.4.2 Insertion probe battery EFM calibration and performance (Chapter 5)

In common with the launch of the new full bore EFM sensor and transmitter a revised battery EFM insertion probe was launched. This probe featured the same pre-amplifier and electronics and, therefore as with the full bore meter, the need existed to characterise the battery EFM probe's calibration both when received new and after use in the field.

Because an insertion probe is capable of being mis-aligned, the scope of the calibration work was extended to cover this and other operator effects, as well as to address the range of overall uncertainty which could be ascribed to the probe's performance.

3.4.3 Meter verification and battery EFM probe velocity profiling (Chapter 6)

The use of the battery insertion probe as part of the water industry's meter verification programme, regulating major water-into-supply meters (WISPY), forms a key role in the delivery of water balance data. Work therefore focused on the need to investigate in detail the performance and limitations of the battery EFM probe, specifically when used as a velocity profiling tool.

A pre-requisite in order to deliver this objective was to improve the data collection and benchmarking of the data being generated by the battery EFM probe when deployed as a velocity profiling tool. This led to the identification of four subsidiary research tasks, namely:

1. the development of a suitable data collection software tool to improve the traceability and quality of data when velocity profiling;
2. the establishment of the accuracy, reproducibility and qualitative performance of the verification technique itself, by measuring baseline velocity profiles at Hams Hall and the probe manufacturer's production plant;
3. the pursuit of field trials, utilising the developed software, targeting representative meter sites (a) to discover weaknesses and sources of error when using the battery insertion probe meter and (b) to demonstrate, quantify and improve on the key elements associated with the meter verification process based on probe profiling, namely: intrinsic probe performance; practical limitations associated with deployment; achievable data quality; and operator process limitations.
4. the investigation of the limitations of the insertion probe in respect of vibration, particularly when profiling in larger pipe sizes, >400mm or at higher velocities i.e. >1.5m/s.

3.4.4 Sensor and Transmitter Stability (Chapter 7)

Unlike the majority of mains powered EFM meter designs, ABB's battery EFM incorporates active pre-amplifier and memory elements within the sensor assembly. In many applications the sensor may be buried, raising concerns about the long term stability of the battery design. On balance the examination of sensor and transmitter stability was judged to be a valid, additional, area to evaluate over the period of the thesis. Whilst this work incorporated checks on the use and possible misuse of the programmability of the battery technology, the principle objective was to examine and assess the stability, performance and calibration of buried battery EFM meters, following an extended period of time in service.

3.5 JUSTIFICATION OF THE EXPERIMENTAL WORK

3.5.1 Literature Survey on Installation and other Field related Effects

Prior to undertaking the laboratory work a review of the literature was made in order to scope the required range of performance testing. One of the most comprehensive sources concerning installation effects was that of the 1988 FLOMIC consortium report by Baker et al [45]. The effect on electromagnetic flow meters of a change in fluid was found in an earlier paper authored by Baker et al, but written with different collaborators [46]. The effects of a single bend were examined by Halttunen [47], who

combined flow profile data with magnetic field data in an attempt to generalise the results. Halttunen's study showed that at 5D a single elbow would generate $\pm 0.5\%$ change and a double bend $\pm 1\%$. At 2D, the values became -1.5% and $\pm 2.5\%$ respectively.

These published results set the general level expected for performance under non ideal pipework conditions. However, despite the weight of past experimental data, it was concluded that laboratory testing of the battery EFM was justified due to the combination of factors comprising (i) a new, reduced area sensor design (ii) the likely improvements from use of digital transmitter measurement techniques and (iii) the lack of performance data specific to water industry pipework installations.

For electromagnetic insertion probes, with the exception of [33], the 1991 Department of Trade and Industry (DTI) flowmetering consortium report, the literature proved not to reference matters of calibration and field application, although Cascetta et al [48] does present an example comparison between mechanical and electromagnetic probe results. However, the depth of information was limited and did not cover battery powered devices of the type being investigated. By contrast, the techniques applicable to insertion profiling are well represented in the recent literature[49].

In regards to questions concerning EFM sensor and transmitter stability the literature lacked practical case studies relevant to the water industry. An attempt by the UK National Engineering Laboratory to quantify ex-service EFM performance [50] had been unsuccessful. Whilst the lack of success concerning this particular project had been primarily due to technical difficulties, it had been and continued to be the case that the UK water companies were unwilling to collectively advance work in this area. The reason for this stemmed from the possible political risks associated with the likely technical outcomes i.e. increased regulatory pressure to improve measurement, leading in turn to greater capital expenditure.

3.6 SUMMARY

The development of a digital battery electromagnetic flowmeter has raised a series of important technical questions which impact upon the quality and accuracy of regulatory measurement data.

In particular, the performance, calibration, limitations and verification of this design of meter require investigation, whether of the full bore type or of the insertion probe variant.

Where the insertion variant is used for indirectly verifying a water company's bulk water-into-supply type meters, investigation is required to assess the attainable limits of performance for the technology, not only in the laboratory but under practical field conditions.

Within the UK, because of the increasingly common practice of burying battery EFM meter sensors, the question of electromagnetic meter reliability, stability and verification requires investigation in order to assure the accuracy of the regulatory data record over the medium and longer term.

The new instrument(s) therefore justify an in depth, structured evaluation of their detailed performance, calibration, limitations, verification and data quality. In turn this will illuminate the policy limits which incorporation of data derived from battery EFM meters may bring to the overall calculation of water balance values.

4. NETWORK METER LABORATORY PERFORMANCE TESTS USING INDUSTRIALLY REALISTIC PIPEWORK CONFIGURATIONS

4.1 OBJECTIVE

The aim of this laboratory work was to evaluate a 100mm EFM, under battery and mains powered excitation modes, when installed in pipework configurations which were industrially realistic. A variety of components and pipework arrangements were assembled in order to generate both ideal and non-ideal hydraulic conditions not previously reported. In addition, a limited number of performance tests were undertaken using a pressure reducing valve (PRV) mounted in line with first the EFM and then a typical Woltmann design mechanical meter.

4.2 BACKGROUND TO TESTING

The scope and design of the tests was conceived because of the lack of independent published information and because all the available manufacturer data was restricted to calibration results obtained under ideal conditions and with laboratory pipework. The testing planned aimed to exercise the EFM, in battery and mains modes, when installed in conditions which were representative of day to day practice found in the water industry i.e. to illustrate industrially realistic rather than “best-case” performance of the technology.

The aims were to investigate:

- (a) compliance with the then current version of the published international ISO 4064 meter performance standard(s);
- (b) comparative differences between the battery and mains excitation mode performances and;
- (c) differences between the battery EFM technology and existing mechanical metering,

To achieve the necessary spread of results, which would illustrate both the absolute and comparative performances typical of that found in water industry practice, testing was planned as a series of sets of trials covering:

- (i) performance in straight pipework;
- (ii) performance under conditions of disturbed flow ;
- (iii) performance with a gate valve (GV) in-line with the meter and
- (iv) performance with a PRV in-line with the meter.

For all tests the use of cement lined ductile iron pipework, in contrast to smooth walled steel pipework, was adopted in order to better represent industrially realistic practice.

The test laboratory pipework arrangements were specifically chosen because, in direct contradiction of the equipment manufacturer’s installation instructions, industry users frequently adopt non ideal arrangements as a result of following “traditional” distribution network practices. Determining the scale of the influence which both the

GV and PRV have on the EFM design, in either excitation mode, thus represented an important research goal. In addition, the comparison PRV tests using an industrial mechanical Woltmann meter design were valuable from a practical perspective because of the lack of published evidence.

4.3 TESTING ARRANGEMENTS AND TEST METHOD

4.3.1 Pipework arrangements and sensor design note

Figure 4.1 illustrates the view through the 100mm diameter EFM sensor, alongside a selection of the flanged, ductile iron, cement lined pipework used to assemble the test section.

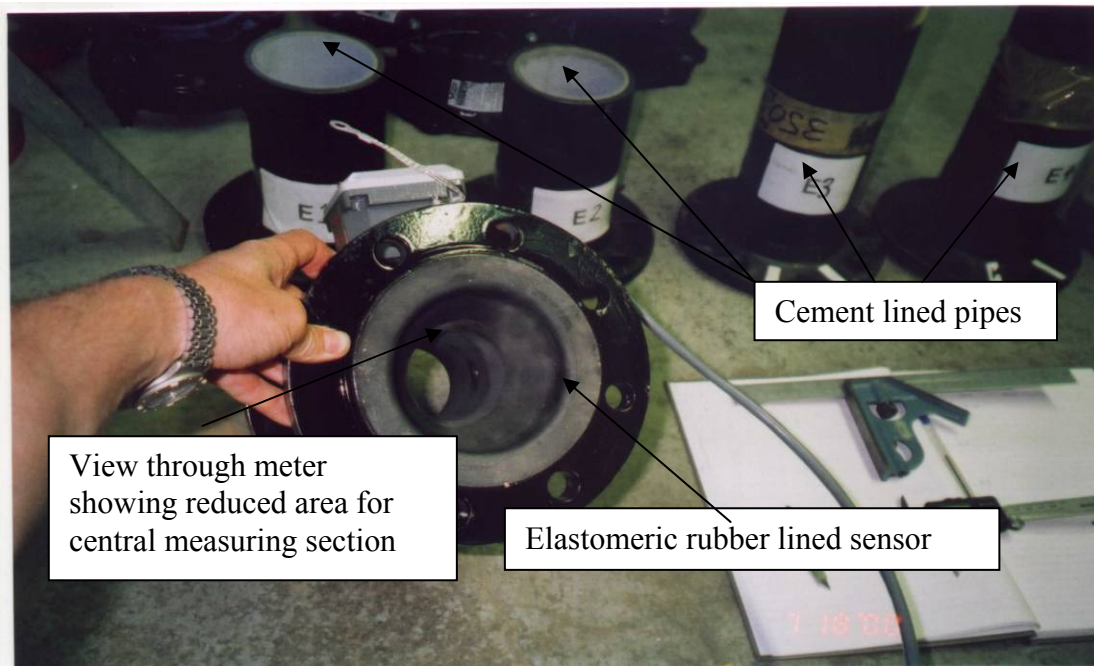


Figure 4.1: Battery meter sensor (100mm) alongside pipework components

Work within the Flow Measurement and Instrumentation Consortium (FLOMIC) Consortium [45] had shown that the combination of asymmetric and swirl flow components can lead to the generation of worst case errors. Further unpublished work by Teijema at Delft Hydraulics, which had been sponsored by the International Instrument Users Association (IIUA) member WIB [51], was followed by a published paper by the same author Teijema [52]. Both the IIUA WIB report and the International Flow Measurement Conference (FLOMEKO) '94 paper documented the effect of pipe fittings and the use of reduced section pipework as a means of modifying non-uniform asymmetric velocity profiles. In the water industry a typical installation, capable of creating asymmetric and possible swirl flow components, is that where a meter is installed in a bypass with 90° bends upstream and downstream of the meter. For this reason the bypass arrangement was selected as the most appropriate configuration to characterise meter performance under difficult, industrially realistic hydraulic conditions.

The test electromagnetic battery meter, installed in a horizontal bypass arrangement, is shown in figure 4.2.

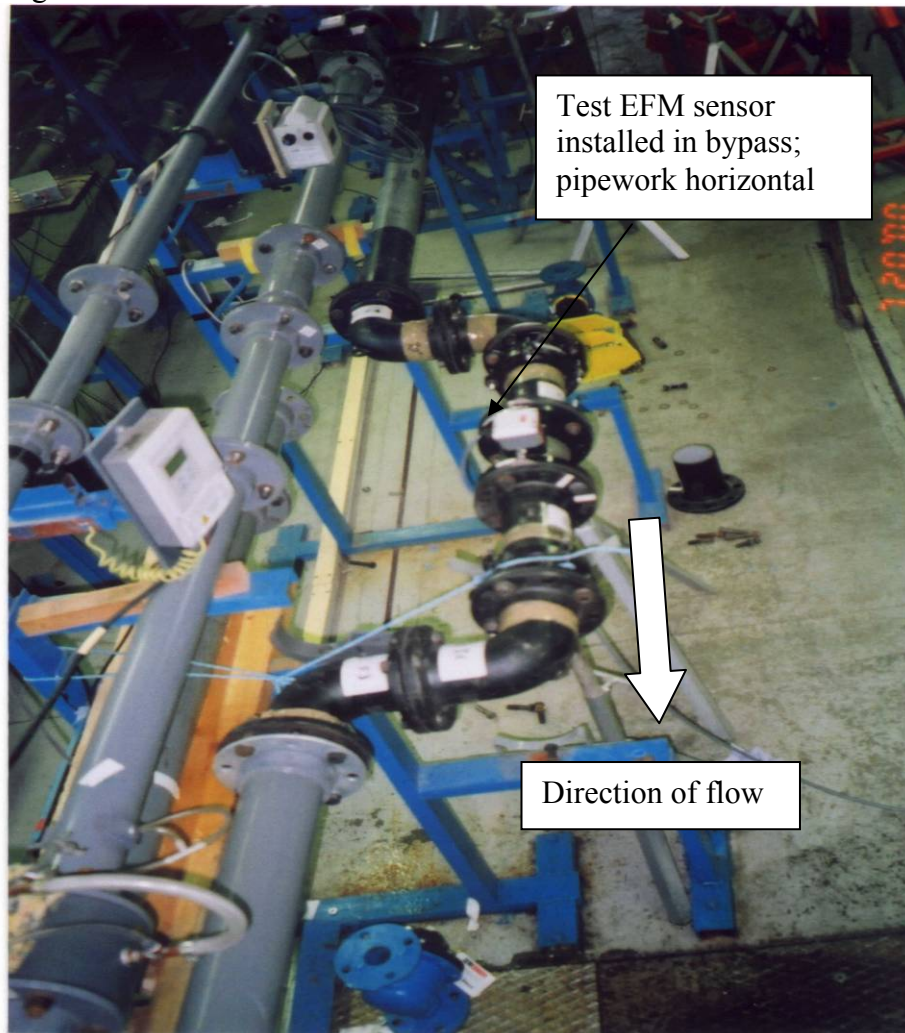


Figure 4.2: Battery meter sensor (100mm) mounted in bypass arrangement

For a number of the bypass arrangement tests, the pipework was rotated by 45° about the axis of flow whilst simultaneously holding the plane of the electromagnetic meter electrodes horizontal. This presented the EFM sensor electrodes with disturbed conditions representing industrially realistic conditions. The rotated arrangement is illustrated in figure 4.3, where it can be seen how the alignment of the pipework bends forces the flow to change direction twice.

Also shown in figure 4.3 is the Cranfield master meter. This was of an older, different, mains powered design, without any reduction in sensor cross section.

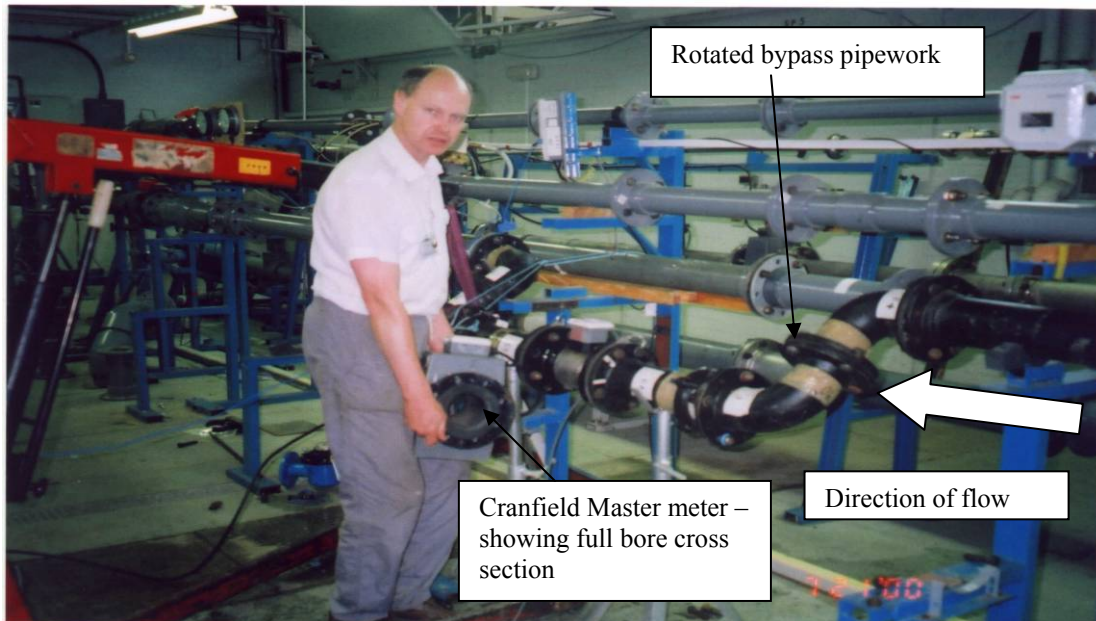


Figure 4.3: Rotated bypass arrangement in Cranfield flow test loop and master meter

Two more installation arrangements were investigated with the EFM. The first arrangement positioned a GV (a) 3.5D upstream then (b) 0D upstream, i.e. bolted to the flange of the EFM. In all tests the GV was installed in the upright position. The second arrangement placed a PRV (a) 5D downstream of the EFM then (b) 0D downstream.

Following the EFM-PRV combination tests the performance of an industrial Woltmann design of mechanical network meter was similarly examined with the PRV. However, the earlier bypass arrangement tests were not repeated with this mechanical meter. Figure 4.4 shows the PRV and mechanical meter installation in the Cranfield laboratory flow rig. This arrangement completed the series of network meter tests in pipework installations which were considered industrially realistic and frequently found in the UK water distribution network.

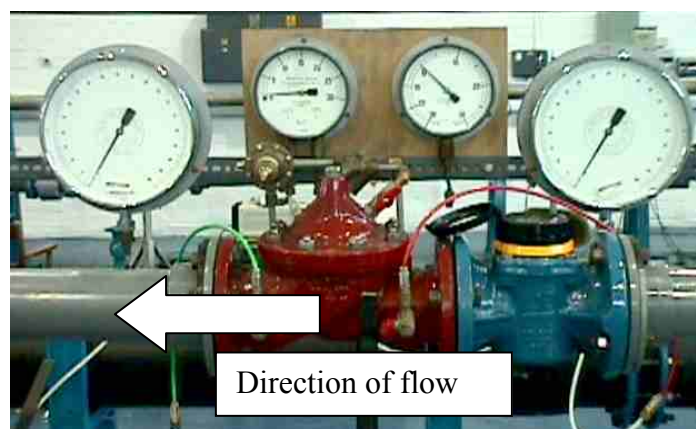


Figure 4.4: Mechanical meter test arrangement with close coupled PRV

4.3.2 Note on reduced area EFM sensor design

The battery EFM design under test incorporated a reduced area design sensor, the appearance of which can be seen in figure 4.5.



Figure 4.5: Battery meter sensor (100mm) showing reduced area design plus digital transmitter

Past work [51, 52] had showed that, generically, reductions in pipeline cross section flatten a given flow profile. Therefore, for the electromagnetic meter design under test it was reasonable to assume that the profile would be made more flat within the meter's central sensor measuring section. When combined with an increase in sensitivity, due to the increased bulk velocity through the reduced measuring section, this type of design was predicted to be better able to measure accurately when subject to adverse hydraulic conditions than unreduced section sensors. A general aim of the testing was to provide the evidence which would support this prediction.

4.3.3 Cranfield laboratory calibration and test method details

At the time of testing the Cranfield flow rig offered either the use of a series of turbine meters or an electromagnetic meter to measure the loop flow. The output of the turbine meters was in the form of high speed pulses, whilst the reference EFM offered both a pulse output, maximum frequency 800Hz, and a nominal 1 second, asynchronous, digital output. The design of the battery EFM pulse output was restricted to a maximum frequency of 50Hz, thus providing insufficient resolution when measuring at low flows to be able to discriminate small differences in performance. Use of the RS232 digital outputs from the battery EFM under test (MUT) and the Cranfield reference meter were therefore chosen as the preferred measurement technique in preference to pulse counting.

To record the data, use was made of the Hyperterminal program [53], provided as part of the Windows NT operating system present on the two, separate, portable computers which were used to log the sensor flow velocity from the master meter and the EFM under test. The requirement to use two separate laboratory PC's was necessary because, at the time, multi-port logging on one machine was technically unrealisable. The data logging of the sensor flow velocities using Hyperterminal resulted initially in the creation of text files for the two meters, which were then imported into a common Excel spreadsheet. This was mounted on a separate analysis PC where velocity was converted to flowrate.

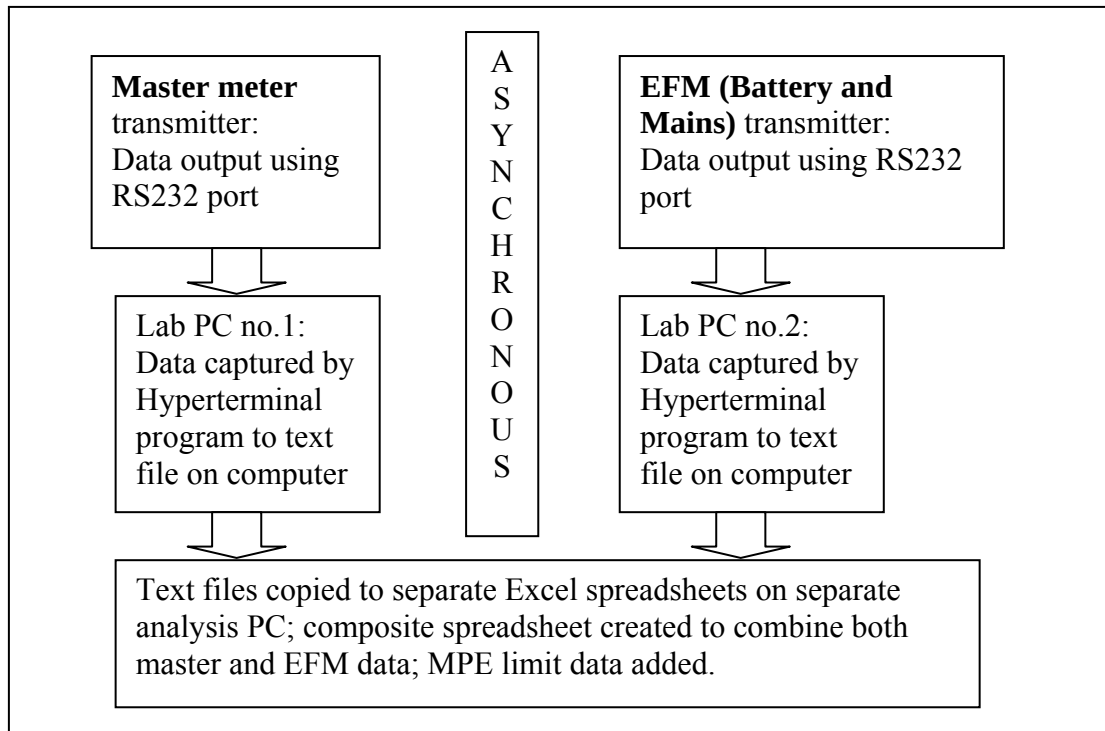


Figure 4.5a: Laboratory method adopted re digital data capture for master and EFM meters

Following the creation of an analysis spreadsheet, additional data relevant to the evaluation of performance, such as individual MPE limits, was added. The complete process is shown in figure 4.5a, with table 4.1 illustrating a typical spreadsheet summary table for one of the test runs.

Test Run Ref.	mm20j10	Test Run Ref.	aq20j10
Meter Ref.	Master	Meter Ref.	100mmAQM
Supply mode	mains	Supply mode	battery
Mean vel(m/sec)	2.129E+00	Mean vel(m/sec)	2.133E+00
Std Dev'n	0.003185165	Std Dev'n	0.003875262
NSE	0.15	NSE	0.18
No of records	1200	No of records	746

Table 4.1: Example of Hyperterminal logged, digitally recorded, EFM data

Shown in Table 4.1 are the data measured for sensor velocity, the EFM excitation mode - battery or mains - and the test run statistics for the simultaneous test runs mm20j10 and aq20j10 which had been logged, using Hyperterminal, on the two separate PC's. The nominal test flowrate through the line was 60m³/hr. Note that NSE is the ratio between the standard deviation and the mean of the dataset and was utilised as a useful measure of the quality and noisiness of the recorded flow data.

Of note is the fact that data from the reference and test flowmeter transmitters was generated asynchronously. This necessarily created different file sizes for the master meter and the battery or mains EFM over any given run time, as can be seen in Table

4.1. If the run times had been short this could have lead to errors arising due to the different absolute start and stop times for the master meter and the battery EFM. In practice, the run times were set nominally to 900 seconds or, for the lower flow runs, 1200 seconds. Runs of this length averaged fluctuations in the Cranfield calibration loop, due to pumping, as well as collecting a large enough dataset to be able to be statistically representative of the average meter performance at the nominal test flow. Similarly the filtering effect of the 3 second internal transmitter time constant, applied to the sensed velocity of both meters, was judged to be of relatively small importance given the deployment of the battery EFM in the water industry as a network meter.

Appendix 4 shows an example of the composite results created from the individual trials.

Use of the direct digital RS232 data stream offered the advantage of eliminating sources of error associated with the conversion of the flow meter transmitter's internal digital flow value to an analogue output. Thus, once measurement of the digital sensor velocity had been adopted, the uncertainty associated with the derived error for the volume recorded by the MUT was dominated by the performance of the reference meter and the number of measurements taken. In pursuance of accurately comparing the performances of the battery and master meter, efforts were concentrated in traceably defining the characteristic of the Cranfield reference meter and then in adequately recording sufficiently large datasets to facilitate meaningful statistical analysis.

Unfortunately, an implicit difficulty was attached to this simple comparative logging strategy because of the mismatch between the turndown (maximum to minimum flowrate) performance of the 100mm Cranfield reference meter - as compared to that of the reduced area design battery EFM. i.e. at lower flows the absolute sensor velocity of the master meter was necessarily lower than the battery EFM being tested, leading to poorer relative accuracy for the same bulk pipe flow. Correction of the calibrated reference meter error characteristic over the flow range being tested was required to overcome this difficulty.

Calibration and correction of the master meter

To establish the performance of the Cranfield reference meter the unit was transported to the Hams Hall laboratory of E.ON and calibrated on the UKAS accredited (laboratory 0031) test rig to an uncertainty of $\pm 0.10\%$. Figure 4.6 shows, for both the linear and mean data-fit characteristics, the meter factor (MF) upper and lower uncertainty limits expressed at the 95% confidence limit. As expected the outer curves are those associated with the mean MF data-fit and the inner curves those associated with the linear data-fit. The graph covers the complete flow calibration range, from 0.1 litres/sec ($0.36\text{m}^3/\text{hr}$) to 16.0 litres/sec ($57.6\text{m}^3/\text{hr}$).

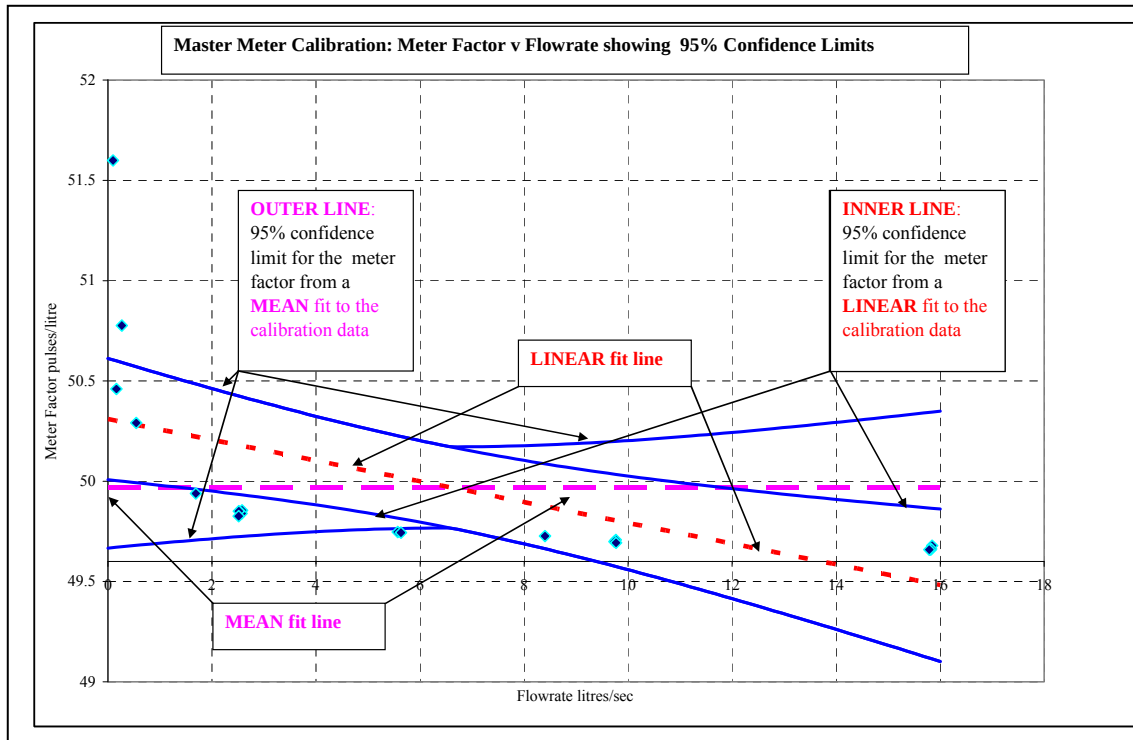


Figure 4.6: Cranfield reference meter (100mm MagMaster) calibration cal'. cert 02798;

The meter factor (MF) set for the reference meter during this UKAS calibration was 50 pulses per litre and figure 4.6 shows the 19 point, uncorrected, meter error curve reproduced from the UKAS calibration certificate (serial no. 02798).

Figure 4.7 shows the summary statistics taken from the calibration certificate describing the assessment of the flow meter uncertainty characteristic. The method used to derive the uncertainties at different parts of the flow range is in line with the UKAS laboratory's calculation method [54], the original approach for which had been created by NEL[55].

Linear characteristic fit to calibration data (including laboratory uncertainty)	At min of range	At mean of range	At max of range
Flowrate litres/sec	0.10	6.58	16.00
Meter factor pulses/litre	50.3049	49.9691	49.4818
Random uncertainty	0.59%	0.39%	0.75%
Total (including lab)	0.60%	0.40%	0.76%
From this calibration: - Uncertainty of meter characteristic over the given range will be no better than:			
Cranfield Reference MagMaster assembly	V00006/9/1		
Meter factor = $A + B \times \text{Flowrate} \pm$	$A = 50.310 \quad B = -5.1747\text{E-}02 \quad U\% = 0.76\%$		

Figure 4.7: Cranfield reference meter (100mm MagMaster) detailed calibration characteristic ref UKAS certificate 02798;

The uncertainty of the linear meter factor characteristic data-fit to the measured flowrate values is a combination of the random uncertainty of the points and the uncertainty of the calibration facility; $\pm 0.1\%$ at Hams Hall. The uncertainty of the mean value for the calibrated meter's meter factor includes, in addition, the bias from the slope of the linear data-fit regression line. Thus the mean data-fit will generate a wider uncertainty band whilst the linear data-fit, which utilises the form of " $a + b \cdot \text{flowrate}$ " to create the characteristic meter factor data-fit, will generate a smaller uncertainty band, illustrated by the inner line.

To assess the Cranfield master meter error over the full class C, ISO4064 specification [56] between the $Q_{\min}$ and Q_n limits required extrapolation of the calibration to cover $0.36\text{m}^3/\text{hr}$ to $60\text{m}^3/\text{hr}$. This returned errors of $+3.12\%$ at $Q_{\min}$ and -0.69% at Q_n .

A method to correct for these master meter errors was therefore necessary. Two alternatives were considered. The first was to analytically fit a curve to the flowrate-error data; the second was to split the meter characteristic into a series of discrete flow ranges, using all of the original 19 data calibration points, and then to apply a linear data-fit to the data within each range. The latter method was chosen because of the utility with which the existing UKAS calibration spreadsheet could be applied to the laboratory data, resulting in a consistent approach throughout.

Following this decision the data were divided into six ranges as showed in Table 4.2.

Flow range (l/s)	Best fit formula ($A + B \cdot \text{flowrate}$) to yield true meter factor (flow rate)	
	A	B
0.095 - 0.267	52.054	-4784.9e-3
0.267 - 0.542	51.247	-1763.6e-3
0.542 - 1.688	50.457	-307.16e-3
1.688 - 2.577	50.125	-110.85e-3
2.511 - 5.631	49.923	-31.747e-3
5.567 - 15.846	49.783	-7.5821e-3

Table 4.2: Best fit formula for calibration curve

At the three high flow ranges, where sufficient data points were available to undertake uncertainty calculations in line with the published ISO methodology adopted for the UKAS certificate [54], the uncertainty of the individual curve fits was estimated as 0.10% , 0.11% and 0.14% respectively. Using this technique the Cranfield master meter errors were corrected across the flow range.

4.4 GENERIC DESIGN STABILITY AND STATISTICS OF TEST EFM AT LOW FLOWS

Evidence concerning the stability of the EFM design both over time and in the short term was sought (a) to gain evidence of the design's calibration stability, (b) to determine typical drift at zero flow and (c) to quantify, by comparison, the effect which

battery operation, in contrast to mains mode operation, had on the quality of the recorded flow data.

Figures 4.8 to 4.12 show the tests undertaken at the manufacturer, ABB [57] and [58]. They illustrate the performance of the basis design on a similar sized (100mm) meter in mains mode (a) following production (b) after leaving the sensor dry for a month and then re-calibrating. The size of the logged test files were, as at Cranfield, nominally either 1200 samples or at the higher flows (greater than Q_n), 900 samples.

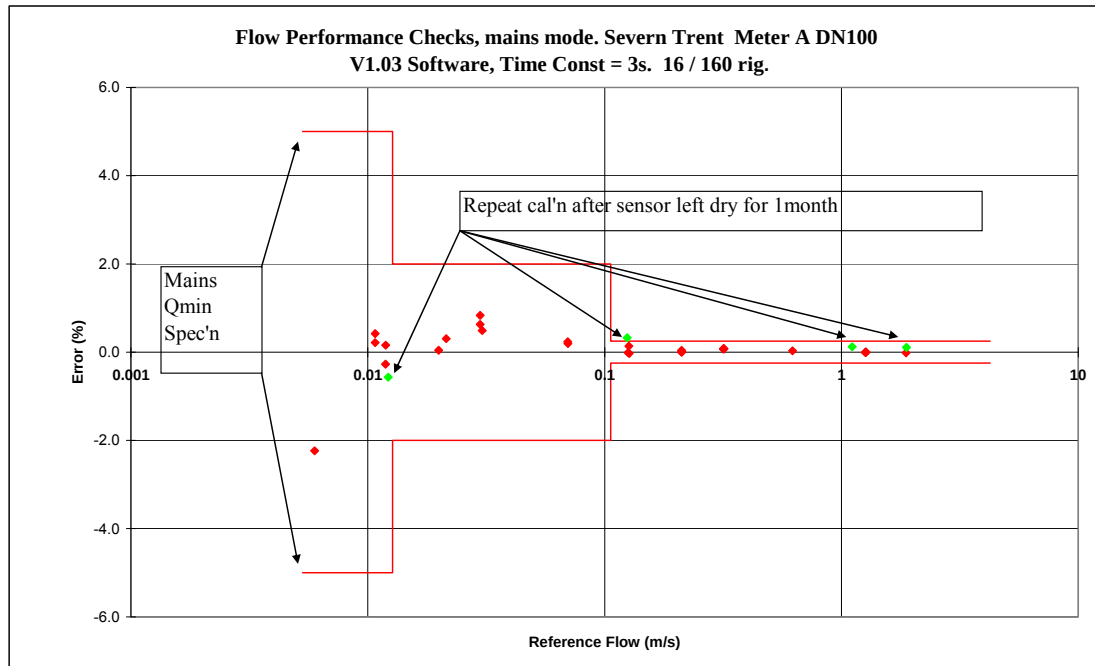


Figure 4.8: EFM calibration stability checks on Severn Trent meter at ABB

Figure 4.9 shows the EFM baseline stability over the short term, 4hours+, by logging the measured flow output at zero pipe velocity. The results indicate that at zero flow the stability, measured as a variation in the zero, can add an uncertainty in terms of absolute velocity terms of around $\pm 0.00015 \text{ m/s}$ ($\pm 0.15 \text{ mm/s}$) for the EFM design being examined.

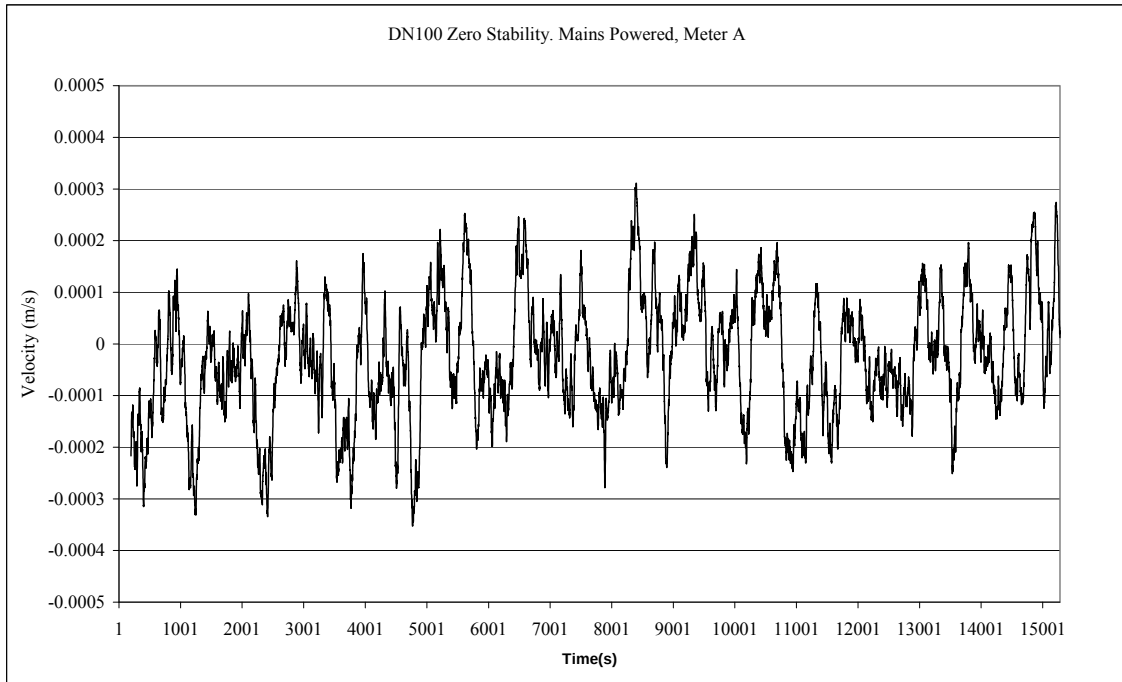


Figure 4.9: Baseline stability check on DN100 Severn Trent meter at ABB

To assess the difference between mains mode and battery mode, additional runs were undertaken covering the specified ISO class C flow range. Figure 4.10 illustrates the comparative qualitative performance for the two modes by plotting the standard deviation (SD) of the measured sensor velocity against itself. As is evident, the battery mode leads to an increase in SD as would be expected given the intermittent sampling employed when in battery mode. The battery excitation mode shows SD ranging between 1.2 and 1.6mm/s compared to 0.8 to 1.0mm/s when mains powered. (In flow units for the 100mm sensor this equates to 0.034m³/hr and 0.045m³/hr respectively).

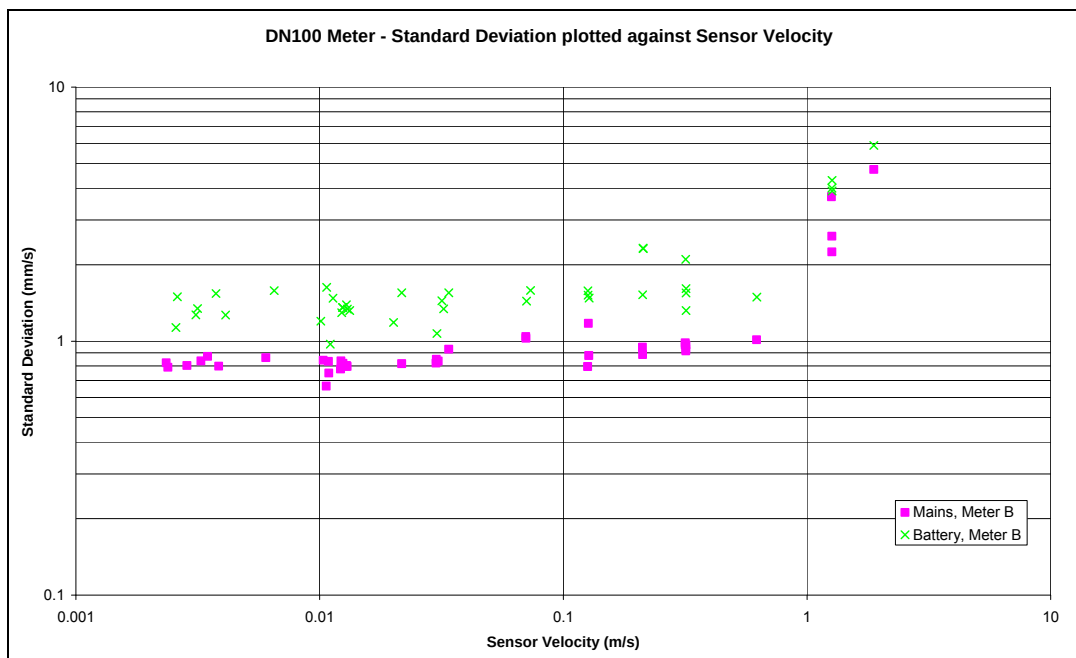


Figure 4.10: Performance of 100mm EFM – flow standard deviation v velocity

A second comparative view between mains and battery modes is given by plotting the normalised standard error (NSE) against velocity. Of interest is the sensitivity of the EFM performance as the sensor velocity falls away at the lower flows, shown in figures 4.11 and 4.12.

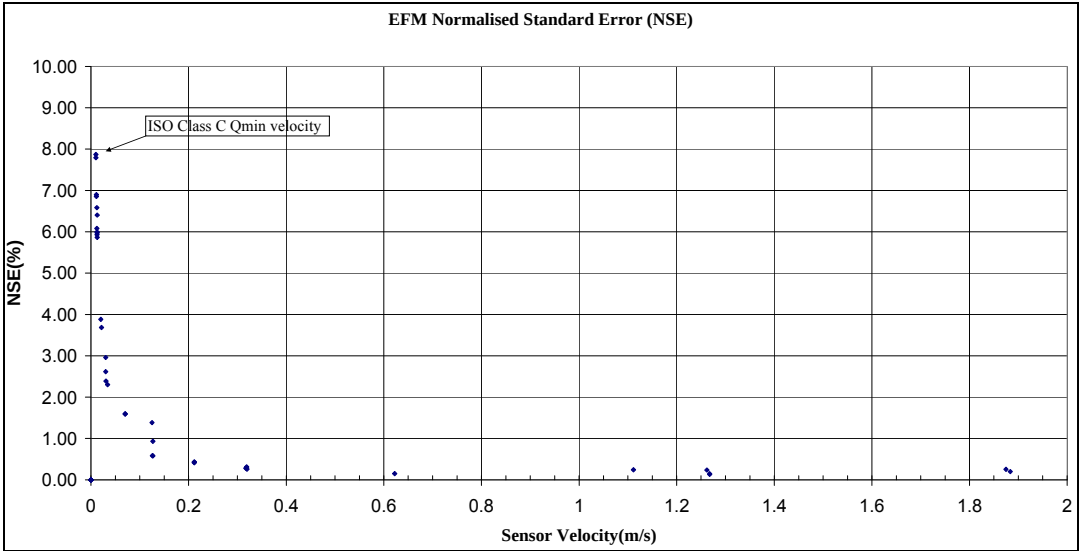


Figure 4.11: Flow NSE v Velocity: 100mm EFM; ISO Class C equivalent range

Figure 4.11 shows a linear plot of NSE performance for the range of velocity equivalent to the ISO class C specification. It illustrates that, for this design, as the velocity decreases below 0.1m/sec the NSE increases sharply as the signal measured at the electrodes is increasingly subject to noise.

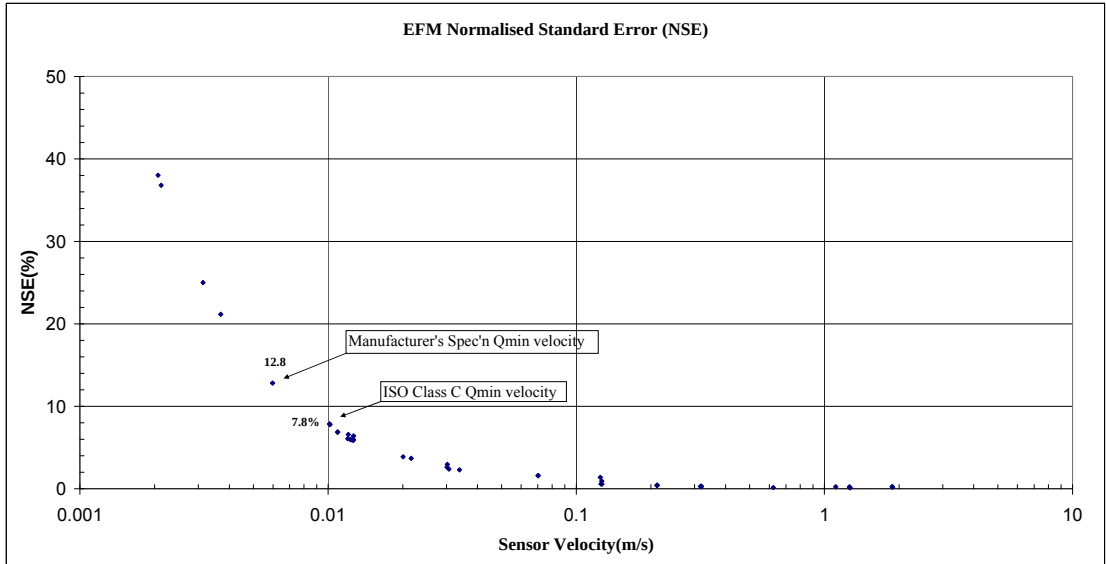


Figure 4.12: NSE Flow v Velocity performance: 100mm ABB EFM Specification

When the minimum flow is decreased yet further, figure 4.12 illustrates that the NSE rises by an order of magnitude, although, as the earlier figure 4.8 showed, the EFM calibration remained within the specification claimed.

The outcome of the tests undertaken to examine the stability of the test EFM indicate that the short term variations in baseline zero are an order of magnitude smaller than the spread of the flow signal at the lower limits of the ISO and manufacturer's specifications. Furthermore, the difference in performance between battery and mains operation, evidenced by the respective plots of the SD for sensor velocity, remained broadly fixed across the range of normal flows. At higher flows the standard deviation increased markedly for both excitation modes, reflecting the increase in flow noise. At lower flows the plot of NSE, defined as the ratio between standard deviation and mean, rises rapidly. This confirmed the view taken that it is essential to expand the number of samples in each test period as the flow becomes smaller, in order to avoid errors created by the increased variability in measured signal.

4.5 CALIBRATION OF EFM AND WOLTMANN METERS IDEAL UPSTREAM AND DOWNSTREAM HYDRAULICS

4.5.1 EFM calibration; battery and mains modes

Figure 4.13 shows a schematic layout of the test arrangement.

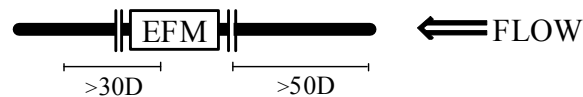


Figure 4.13: Meter test arrangement for ideal U/S and D/S pipework

Figures 4.14 and 4.15 show the performances of the EFM when installed in straight pipework of >50diameters upstream and >30diameters downstream.

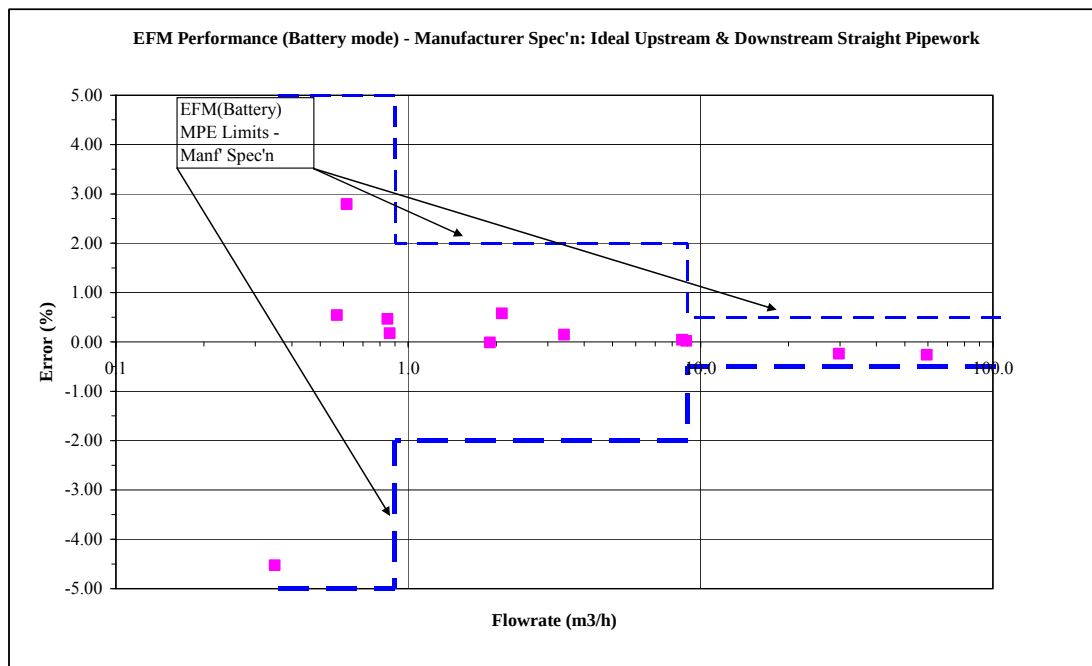


Figure 4.14: EFM performance - battery mode: ideal U/S and D/S pipework

The EFM in battery mode met the manufacturer's maximum permissible error (MPE) claims even when operating below the published Qmin limit of 0.15m³/hr.

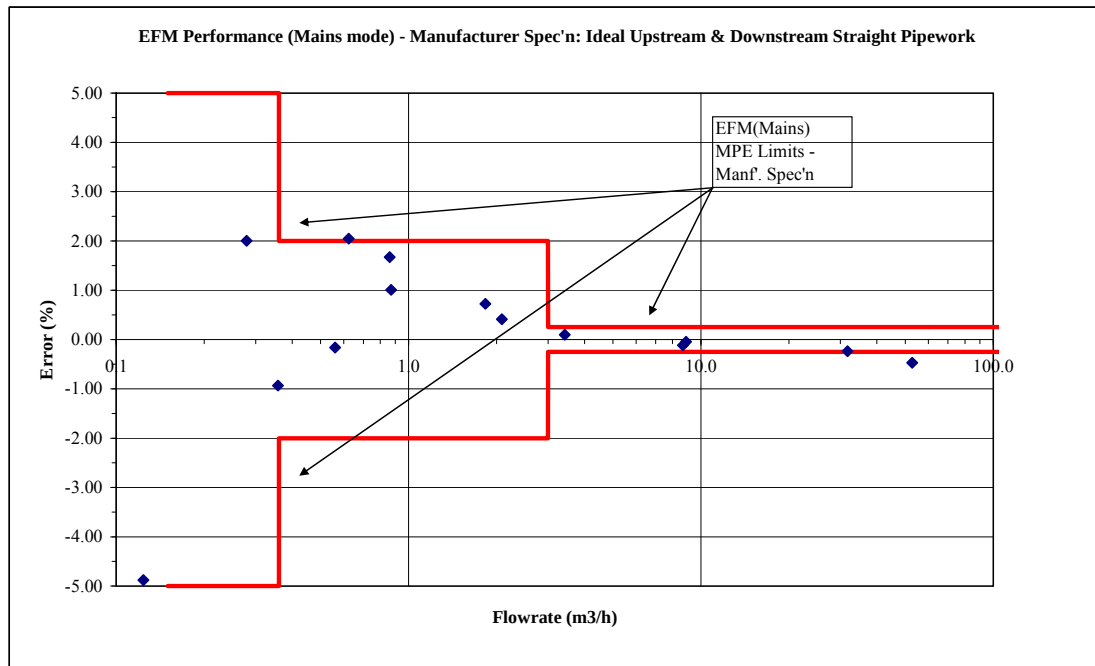


Figure 4.15: EFM performance - mains mode: ideal U/S and D/S pipework

However, in mains mode the EFM failed to remain entirely within the tighter MPE applying to mains operation, recording a single point which lay outside the manufacturer's MPE of +/-0.25%.

The specific error measured was at 0.47% at a flow of 52.78m³/hr, slightly below the ISO class C Qn value of 60m³/hr. Nevertheless, because the ISO specification is +/-2% the EFM can only be said to have failed the manufacturer's own performance statement. Referring to figures 4.10 and 4.11, the standard deviation and NSE (recorded at the manufacturer at a similar flowrate equivalent to 1.8m/sec), were 4.75mm/s and 0.20% respectively. Given that these factory results were at a flow close to the Cranfield test flow of 52.78m³/hr, the indication is that at higher flows the manufacturer's error limits may be expected to be reached or exceeded.

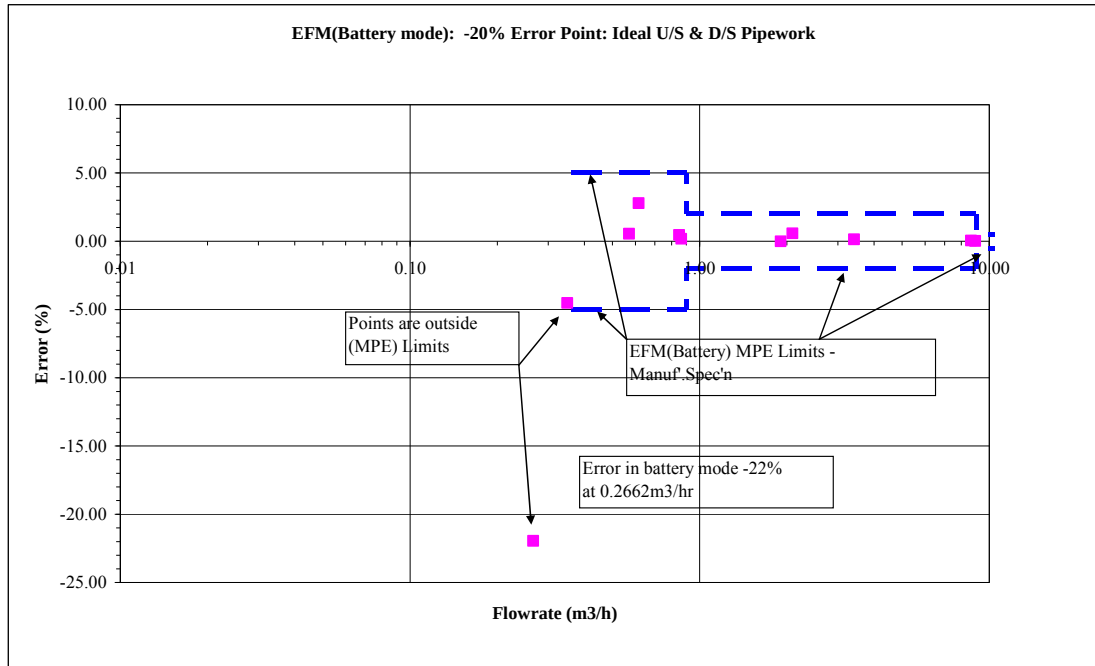


Figure 4.16: EFM -20% error point in battery mode: ideal U/S and D/S pipework

Because of the importance performance difference observed between battery and mains operation the tests were extended to determine at what flow a nominal 20% error would occur for the two excitation modes. The 20% limit was chosen because the water balance calculations may, within the OFWAT data classification bands validly include measurements whose stated error limit lies within $\pm 20\%$.

Figure 4.16 illustrates the result of the extended low flow tests in battery mode. It shows an error of -21.95% at $0.2662\text{m}^3/\text{hr}$. The test time was approximately 20 minutes, with nominally 1200 samples collected, asynchronously, at approximately 1 second intervals.

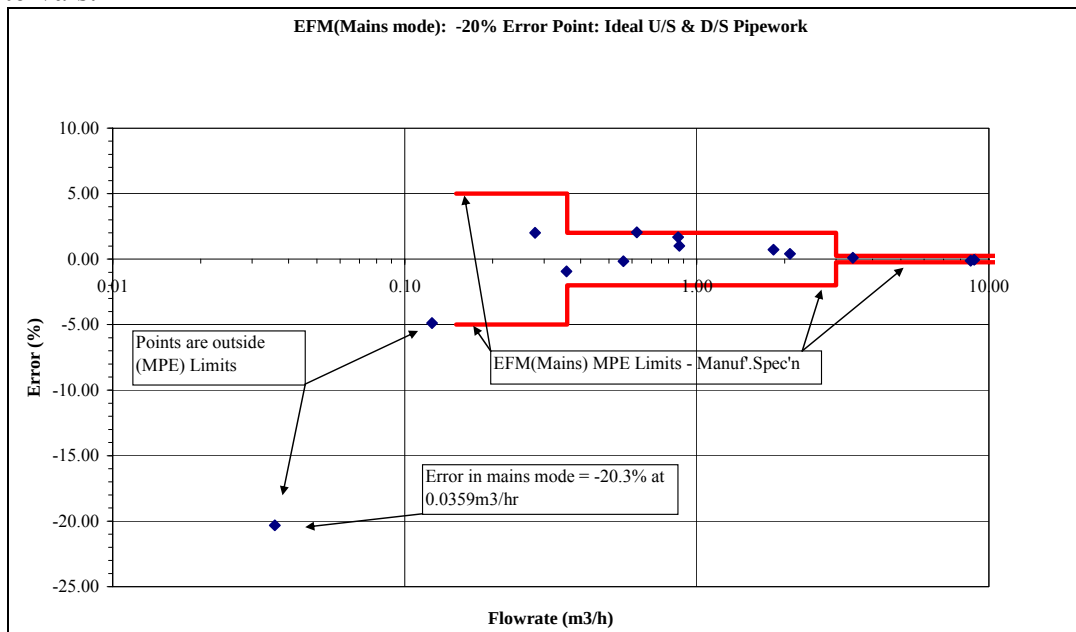


Figure 4.17: EFM -20% error point in mains mode: ideal U/S and D/S pipework

Figure 4.17 illustrates the test results for the same EFM in mains mode, showing an error of -20.32% at 0.0359m³/hr. Comparing the two results the experiment revealed that for a nominal specified error of -20%, the battery operated unit will reach the 20% limit at a flow x7.4 higher than when operated in mains mode.

4.5.2 Woltmann meter calibration

Because the experimental work using a mechanical meter was focused on generating only a limited set of comparison data over a restricted range of flows, the flowrate range of the calibration was intentionally limited. The range chosen was from Qt to Qn, (the transitional to the nominal flowrate), for a 100mm. class C, ISO specified meter; namely 2m³/hr to 60m³/hr.

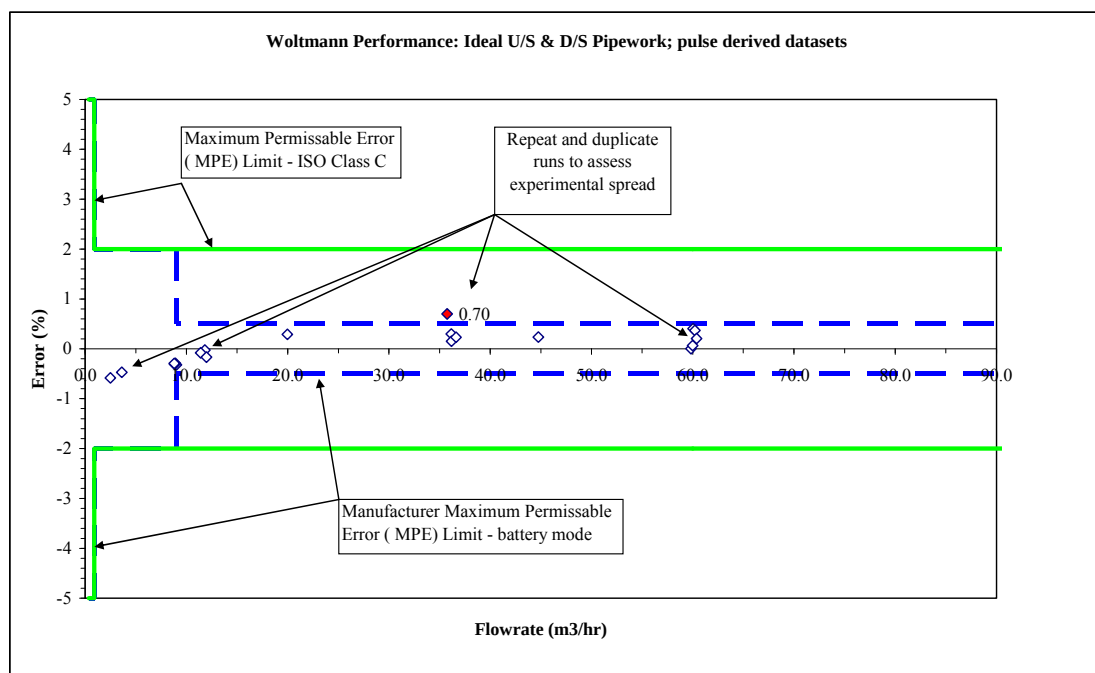


Figure 4.18: Woltmann meter performance: ideal U/S and D/S pipework

As figure 4.18 shows, the mechanical Woltmann meter design performed within the ISO class C MPE limits but failed to remain within the much tighter $\pm 0.5\%$ battery EFM MPE limits specified in the upper zone of the meter's operating range. (Observe the +0.70% meter error point shown on the graph in red, which exceeds the $\pm 0.5\%$ limit).

Nominal Flowrate (m3/hr)	No. of repeat runs	Mean Flow (m3/hr)	Max - Min Range (%)		Std Deviation	NSE (%)
60	5	60.22	0.5%	-0.7%	0.287	0.5%
36	4	36.30	1.1%	-0.8%	0.291	0.8%
12	3	11.72	2.0%	-2.7%	0.288	2.5%
9	4	8.86	1.4%	-1.0%	0.093	1.1%

Table 4.3: Woltmann calibration measurement statistics

However, the experimental statistics for the calibration runs, shown in tables 4.3 and 4.4, indicate that the inability of the mechanical meter design to fully meet the tighter battery EFM MPE limits should be regarded as a marginal failure, due to variability in the test technique.

Nominal Flowrate (m ³ /hr)	Meter Error (%)	Max - Min Meter Error Range (%)		Meter Error Span	Meter Error Std Dev
60	0.21	0.40	0.01	0.40	0.18
36	0.35	0.70	0.15	0.55	0.24
12	-0.09	-0.02	-0.17	0.14	0.07
9	-0.30	-0.29	-0.32	0.03	0.01

Table 4.4: Woltmann meter error statistics

As the tabulated data shows, the variation in the test flowrate range is acceptable, falling within the +/-5% allowed by the standard. In contrast, the span for the meter errors at 36m³/hr of 0.55%, when taken together with the standard deviation of 0.24% for the grouped data, illustrates that the spread on the recorded data limits is significant. One cannot therefore conclude, on the evidence of a single failure measurement, that the mechanical meter design is intrinsically incapable of achieving the battery EFM performance.

4.5.3 EFM Repeat calibrations for PRV testing

The primary aim of the PRV tests was to produce data allowing the performance of the mechanical and EFM meters to be compared. Hence, it was essential to derive performance curves which had been measured in a similar manner. However, because determination of the mechanical meter flowrate necessarily requires use of a pulse output, the earlier EFM calibration results, which had used that design's digital output, did not meet the like-for-like criteria. A series of repeat calibration runs were therefore undertaken in order to be able to use like-for-like datasets. Figures 4.19 and 4.20 illustrate the results.

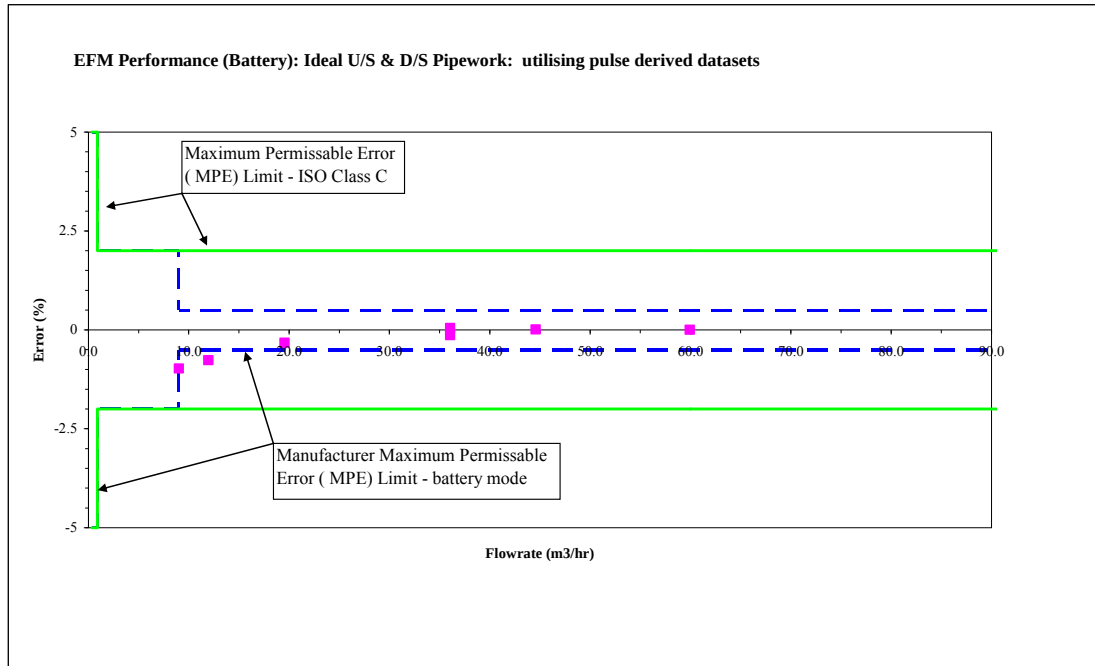


Figure 4.19: EFM performance (battery): Ideal U/S and D/S pipework: pulse derived datasets

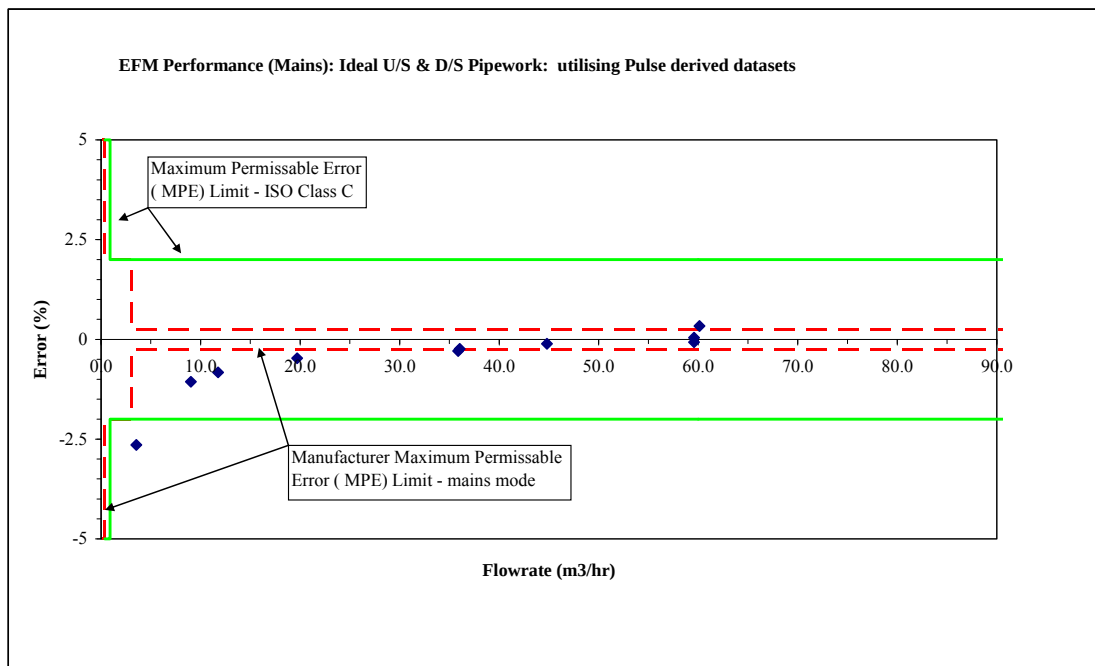


Figure 4.20: EFM performance (mains): Ideal U/S and D/S pipework: pulse derived datasets

The data indicate the EFM calibration performance when using the pulse, not digital output, differed from earlier trials and did not fully meet either the manufacturer's specified MPE for either battery or mains operation, nor in the case of the mains mode EFM, the ISO Specification MPE. The decision to recalibrate the EFM so that like-for-like logged data derived from pulse inputs could be used when comparing the EFM performance against the PRV was therefore technically justified. No further investigation was made of the differences between the pulse output and the digital output because, when informed of the performance results, the manufacturer indicated

that improvements had been made to the particular design to overcome reported non linearity associated with the pulse output [59].

4.6 PERFORMANCE OF EFM AND WOLTMANN METERS USING INDUSTRIALLY REALISTIC PIPEWORK AND COMPONENTS

4.6.1 Test plan and MPE performance limits

The laboratory tests investigated the performance of the EFM when operated with the meter installed in two industrially realistic pipework arrangements and then in conjunction with two flow control components; namely a gate valve (GV) and a pressure reducing valve (PRV).

The first set of tests evaluated EFM performance when installed in the bypass configuration previously illustrated. Three bypass pipework variants were tested:

- (1) with the bypass horizontal
- (2) with the bypass rotated by 45 degrees but with the plane of the meter's measuring electrodes kept horizontal and
- (3) as for (2) but with a GV introduced directly upstream of the meter.

The second set of tests dispensed with the bypass, using straight pipework and examined changes in EFM performance when a PRV was added to the line. As an adjunct to these EFM tests a similar set of runs were conducted using a mechanical meter. These allowed comparison between the newer EFM battery technology and a commonly installed PRV arrangement which uses a mechanical meter design.

The composite limits of performance, which includes maximum permissible error (MPE) limits, against which all test results for the electromagnetic meter were to be compared, whether in battery or mains powered mode, were taken from Part I of the international standards organisation publication ISO 4064, supplemented by the manufacturer's own limits. These limits are tabulated in Appendix 5 which shows possible MPE combinations. The graphs which follow are shown with the ISO and/or appropriate manufacturer MPE limits super-imposed. Battery MPE and mains (Vac) MPE are shown separately.

Note that for the EFM the MPE limits are smaller than those for the mechanical meter equivalent.

4.7 RESULTS OF EFM AND WOLTMANN METER PERFORMANCE TESTS: CRANFIELD LABORATORY

4.7.1 Performance when installed in standard bypass configuration: straight upstream and downstream pipework

Figure 4.21 shows a schematic layout of the test arrangement.

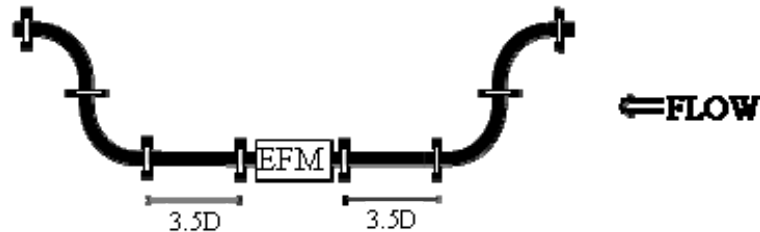


Figure 4.21: Meter test arrangement standard bypass configuration: - meter horizontal; pipework horizontal; bends 3.5D U/S and D/S

The results for the battery electromagnetic meter installed in the bypass configuration with the pipework and meter electrodes in the horizontal plane and the bends at 3.5D upstream and downstream, are shown in figure 4.22.

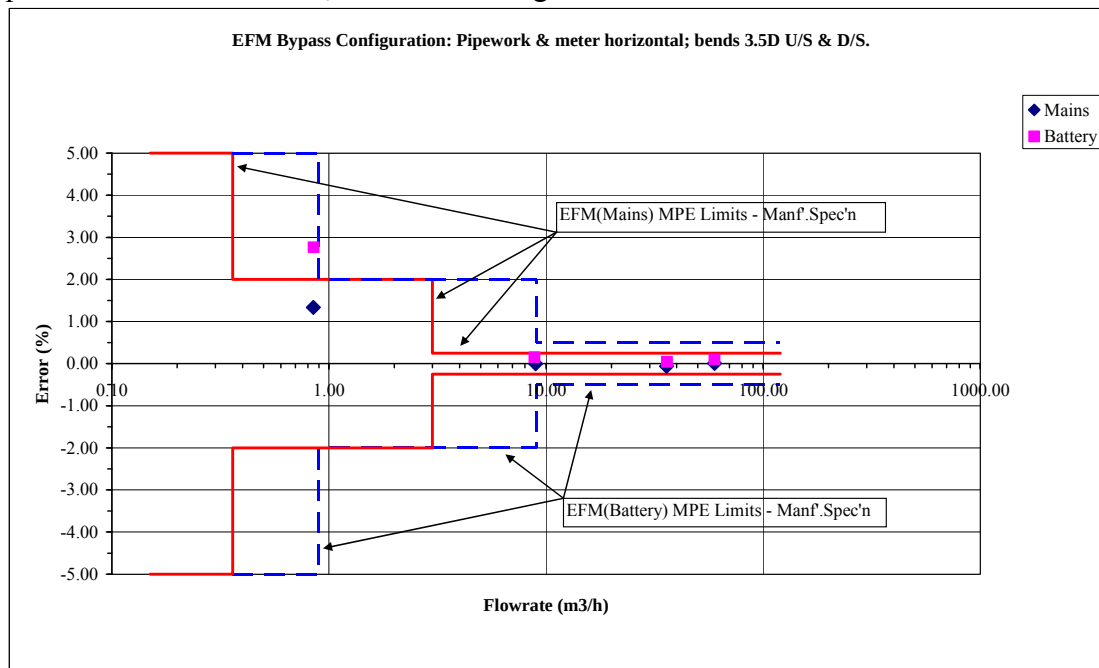


Figure 4.22: EFM in bypass: pipework and meter horizontal; bends 3.5D U/S and D/S.

The performance of the EFM, subject to the number of points tested, remained within the ISO 4064 class C limits, as well as meeting the manufacturer's enhanced MPE claims, when excited in either mains or battery powered mode.

4.7.2 Performance when installed in rotated bypass

Figure 4.23 shows a schematic layout of the test arrangement.

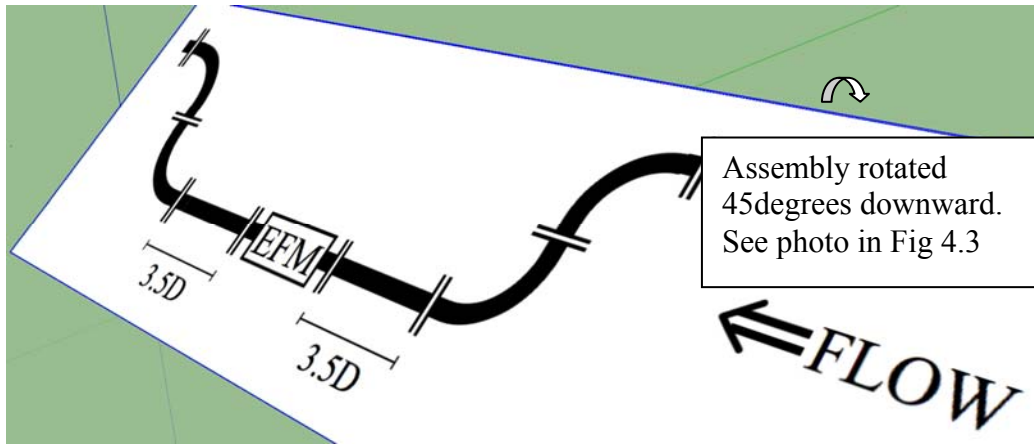


Figure 4.23: Meter test arrangement rotated bypass configuration: - meter horizontal; pipework rotated 45°; bends at 3.5D U/S and D/S

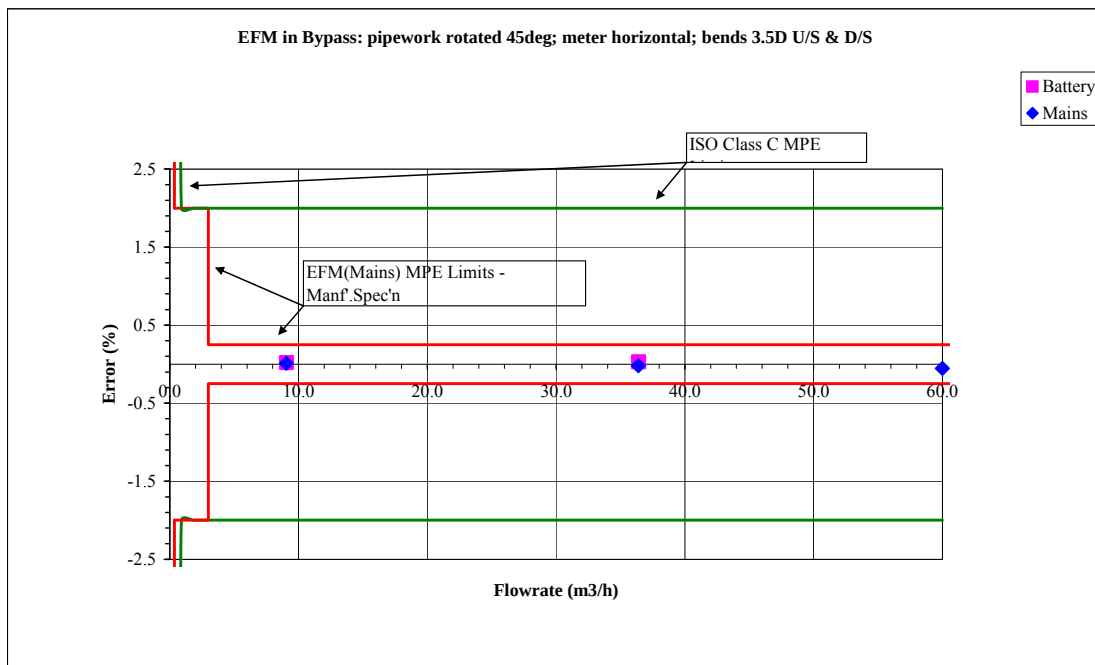


Figure 4.24: EFM in Bypass: pipework rotated 45°; meter horizontal; bends 3D U/S and D/S

The performance of the electromagnetic meter remained within the ISO 4064 class C points tested, as well as meeting the manufacturer's enhanced MPE claims, when excited in either mains or battery powered mode. The additional hydraulic effects, created by rotating the bypass assembly, did not cause the meter's performance to degrade despite the complex hydraulic conditions. The available laboratory time did not allow for additional testing at lower flows, as had been possible with the straight pipework configuration.

4.7.3 Performance when installed in rotated bypass with GV 3.5D upstream

Figure 4.25 shows a schematic layout of the test arrangement.

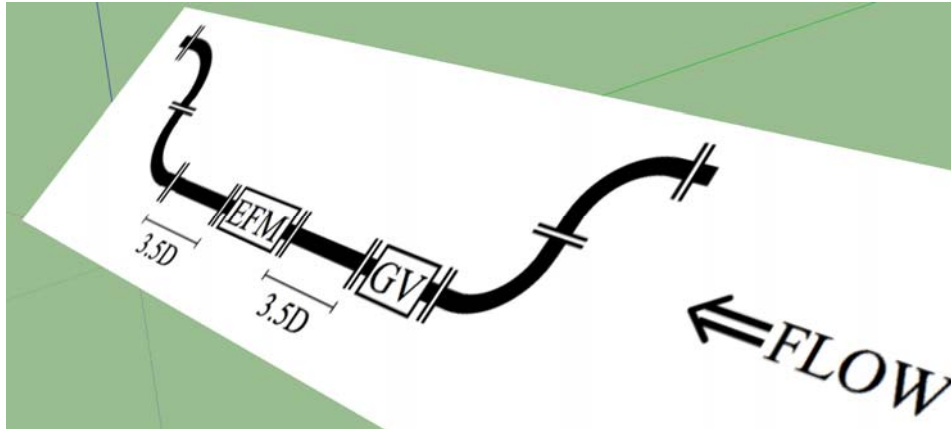


Figure 4.25 Meter test arrangement bypass with GV 3.5D upstream: - meter horizontal; pipework rotated 45°; bends at 3.5D U/S and D/S

The results for the above installation arrangement are tabulated in table 4.5. The gate valve, installed in the vertical position, required 14 turns from fully open to fully shut. Noting that a gate valve is essentially an isolating device, the three gate positions chosen represent those most likely to be found in day to day use, namely: (a) fully open; (b) not quite fully open; (c) not quite fully shut.

Flow rates (m ³ /h)		Gate valve	Error (%)	
Mains powered	Battery powered		Mains powered	Battery powered
61.76	61.06	Fully open	+0.10	-0.29
No test/61.61	61.61	Fully open	-	+0.08
61.58	61.57	4 turn shut	+0.05	-0.25
57.12	57.16	10 turn shut	-0.14	-0.51

Table 4.5: Bypass configuration - meter horizontal, pipework rotated, GV at 3.5D U/S

The performance of the electromagnetic meter, in either mains or battery mode, remained well within the specification of class C but marginally exceeded the manufacturer's own MPE, of +/-0.5% by 0.01%, for one point when battery powered.

Because of this failure, further tests, deliberately including repeat runs, were undertaken but only for the most common mode - battery powered. The results are tabulated in table 4.6 and illustrated in figure 4.26.

Flow rates (m ³ /h)		Gate valve	Error (%)	
Mains powered	Battery powered		Mains powered	Battery powered
-	59.91	Fully open	-	+0.20
-	59.89	Fully open	-	-0.10
-	36.21	Fully open	-	+0.08
-	36.16	4 turn shut	-	-0.02
-	35.33	10 turn shut	-	-0.06
-	9.03	Fully open	-	+0.47

Table 4.6: Bypass configuration - meter horizontal, pipework rotated, gate valve at 3.5D upstream (battery only)

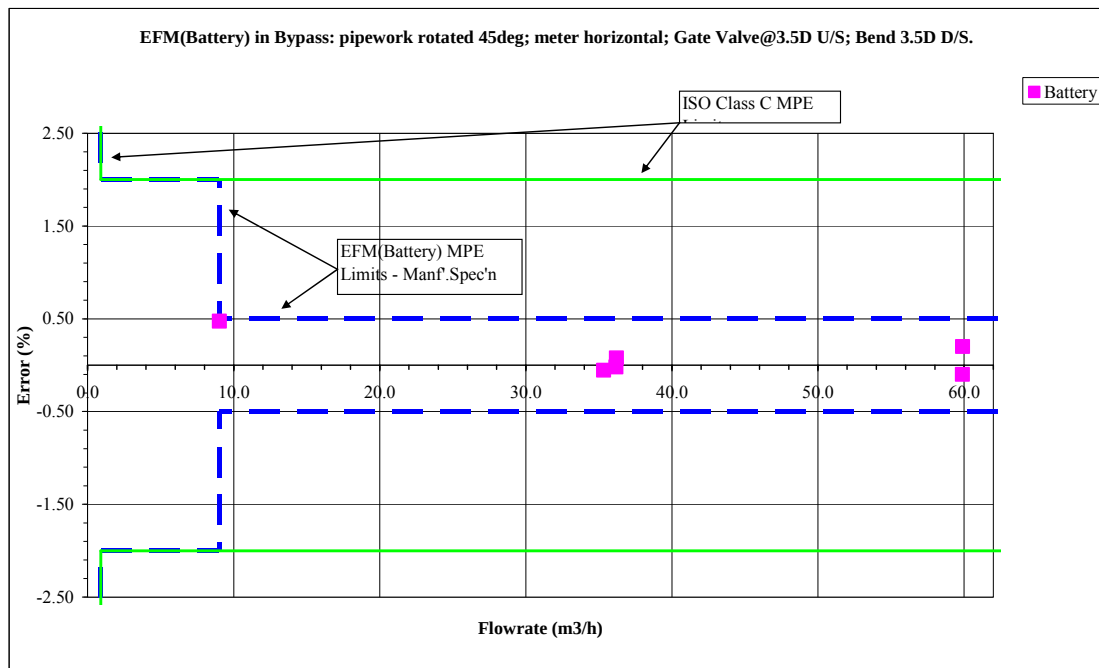


Figure 4.26: EFM (Battery) in Bypass: pipework rotated 45°; meter horizontal; Gate Valve @ 3.5D U/S; Bend 3.5D D/S

The additional tests confirmed EFM performance within Class C MPE limits but illustrated that it is not possible, under battery operation, to confidently state the performance to be better than $\pm 0.5\%$.

This finding led to the conclusion that, within the limits of the testing regime adopted which used test run times of the order of 600seconds or longer, it was not possible to directly link EFM performance to a particular fitting or disturbance.

4.7.4 Performance when installed in rotated bypass with GV 0D upstream

Figure 4.27 shows a schematic layout of the test arrangement.

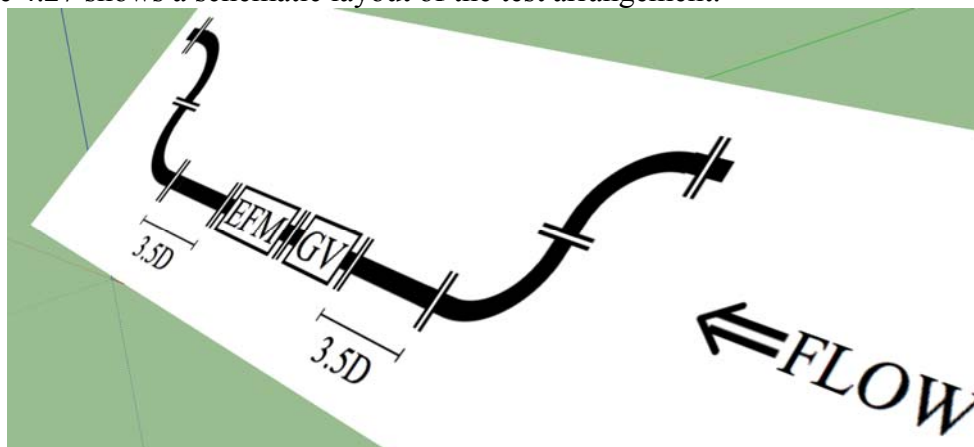


Figure 4.27 Meter test arrangement rotated bypass with GV 0D upstream: meter horizontal; pipework rotated 45°; bends at 3.5D U/S and D/S

The results for the above installation arrangement are tabulated in table 4.7 and illustrated in figure 4.28.

Flow rates (m ³ /h)		Gate valve	Error (%)	
Mains powered	Battery powered		Mains powered	Battery powered
60.66	60.68	Fully open	-0.08	-0.30
34.49	34.62	Fully open	-0.11	-0.23
34.48	34.49	1 turn open	-0.10	+0.25
No test	34.49	2 turn shut	-	-0.22
34.47	34.92	4 turn shut	0.15	-1.23
33.78	33.78	10 turn shut	1.81	1.41
8.87	8.91	10 turn shut	1.87	1.59
8.87	8.86	Fully open	-0.17	-0.35

Table 4.7: Bypass configuration - meter horizontal, pipework rotated, GV 0D U/S

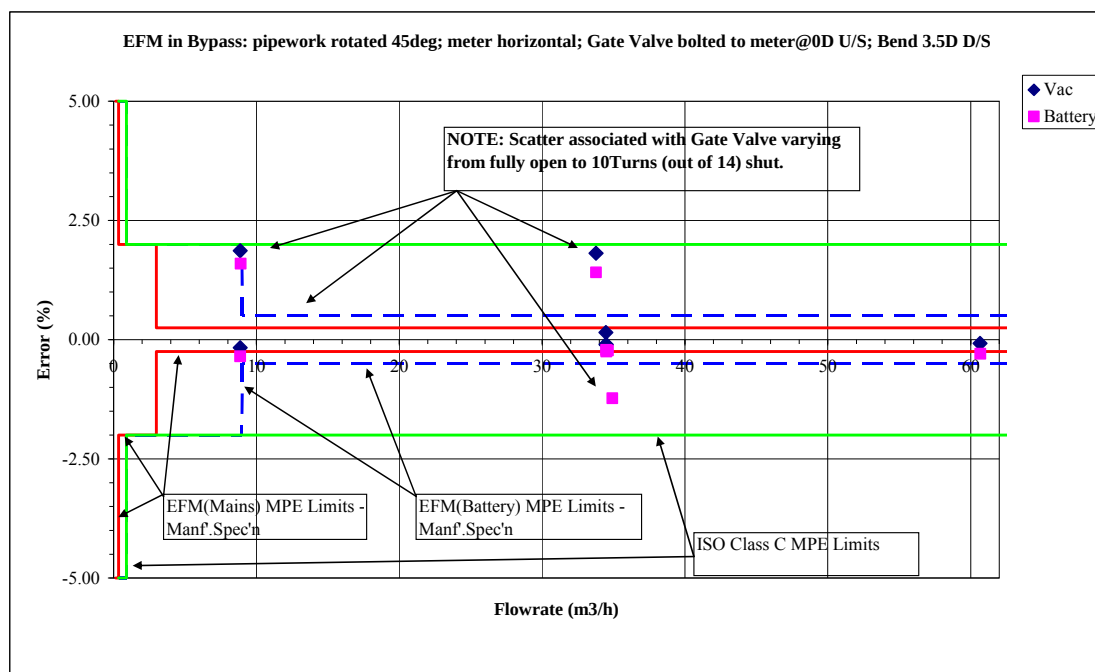


Figure 4.28: EFM in bypass; pipework rotated 45°; meter horizontal; GV bolted to meter @ 0D U/S; bend 3.5D D/S

In contrast to previous results, where with the gate valve bolted 3.5D upstream the EFM exhibited lower errors in mains mode than in battery mode, bolting the gate valve directly to the meter flange induced marginally better performance from the battery mode at two points. Given that the manufacturer specifically advises against such close coupling of large metallic and magnetic masses one can speculate that the addition of the gate valve may have been sufficient to alter the weight function of the meter. Another contributory source of error will be the profile distortion introduced by the gate's intrusion into the pipe, although this may be lessened by the reduced area design's potential to make the profile flatter. However, despite these potential effects the differential movement in the error was small.

The key observation for this close coupled gate valve and EFM combination is the scale of the spread of results which result from exercising the gate valve between fully open

to almost closed: +1.91% and +1.64% for mains and battery modes respectively. Even under these highly disturbed conditions the performance of the EFM remained within the MPE limit of ISO 4064, irrespective of the excitation mode; subject to the number of points tested. In contrast, the manufacturer MPE limits were exceeded whether in battery or mains powered mode.

4.8 PRV TESTING: EFM(mains), EFM(battery) AND WOLTMANN

In a water distribution system flow meters are often installed close to pressure reducing valves (PRV's). The performance of the flow meter could thus be affected by the PRV with the effect depending on several factors, of which proximity to the meter and valve opening are of high importance. In spite of the importance of meter readings in water management there had been no independent study to quantify such PRV effects. The aim of the Cranfield laboratory work was therefore to fill this gap in knowledge, including contrasting battery and mains powered EFM performance.

For the study a commonly used 100mm PRV manufactured by Claval was used in conjunction with another commonly installed Woltmann style meter made by Elster, the Helix 4000.

4.8.1 Data Acquisition and Analysis Method:

PRV, EFM and Mechanical Meter Testing Combinations

In contrast to the earlier use of digital data transmitted from the master and test meters using RS232, the PRV series of tests derived flow data from recording meter pulse output streams. Figure 4.29 shows the methodology in schematic form.

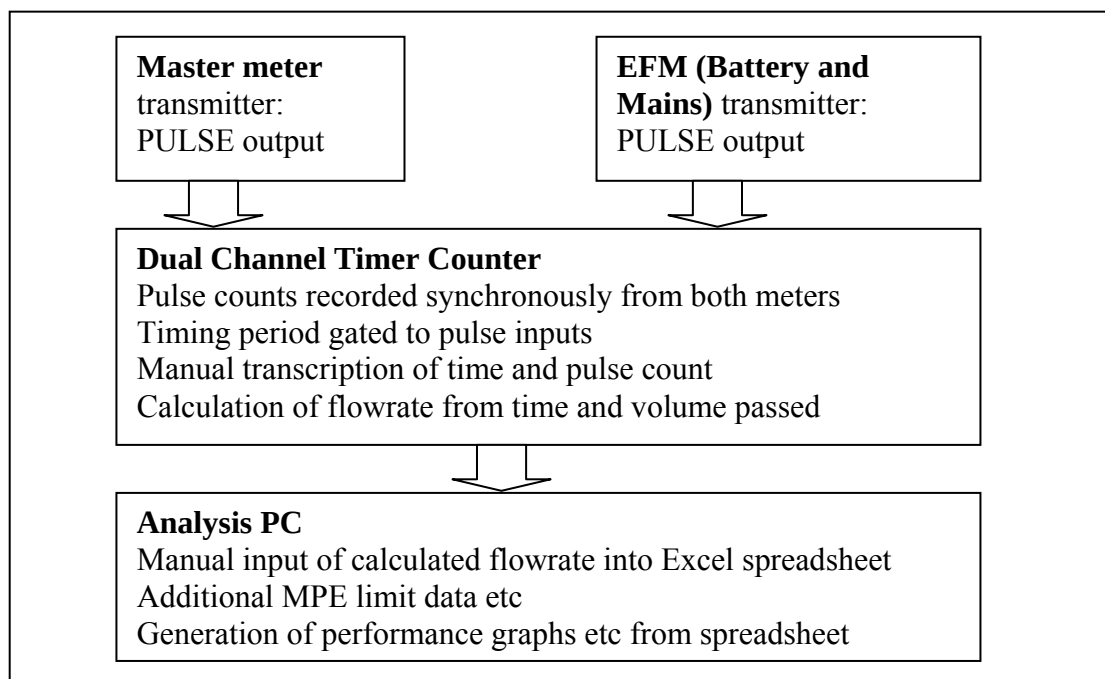


Figure 4.29: Method of data acquisition and analysis for PRV testing

For the mechanical meter the source of pulses was a standard manufacturer produced pulse unit attached to the mechanical meter index, which itself was coupled magnetically to the internal rotating Woltmann mechanism. In the case of the EFM the pulse train was generated from an open collector switch incorporated in the transmitter electronic design.

4.8.2 Schedule of tests – PRV, EFM and mechanical meter combinations

Following establishment of the baseline error curves for the two selected test meters, a 100mm EFM and 100mm Helix 4000 Woltmann mechanical meter, the individual performances of each instrument were measured:

- (a) spaced at a distance of $x5D$ from the PRV and
- (b) directly coupled to the PRV

In both configurations the MUT was located upstream of the PRV, in line with common water industry practice, as illustrated in figure 4.4. Table 4.8 lists the test schedule.

Test No.	Meter type and operational mode	Description of test
1	EFM(mains)	PRV 5D downstream of meter flange
2	EFM(battery)	PRV 5D downstream of meter flange
3	Mechanical	PRV 5D downstream of meter flange
4	EFM(mains)	PRV bolted onto downstream meter flange
5	EFM(battery)	PRV bolted onto downstream meter flange
6	Mechanical	PRV bolted onto downstream meter flange

Table 4.8: PRV schedule of tests; EFM and mechanical meters

4.8.3 EFM (mains) performance; PRV 5D downstream of flange

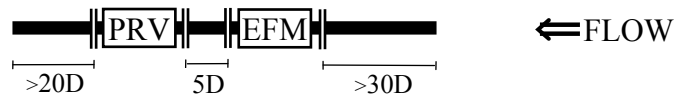


Figure 4.30: Meter test arrangement: meter horizontal; pipework horizontal; PRV 5D D/S of EFM(mains)

The evidence shows that the spread of results seen with the PRV fitted in line, 5D downstream, is similar to that seen for the repeated tests made during the baseline calibration runs.

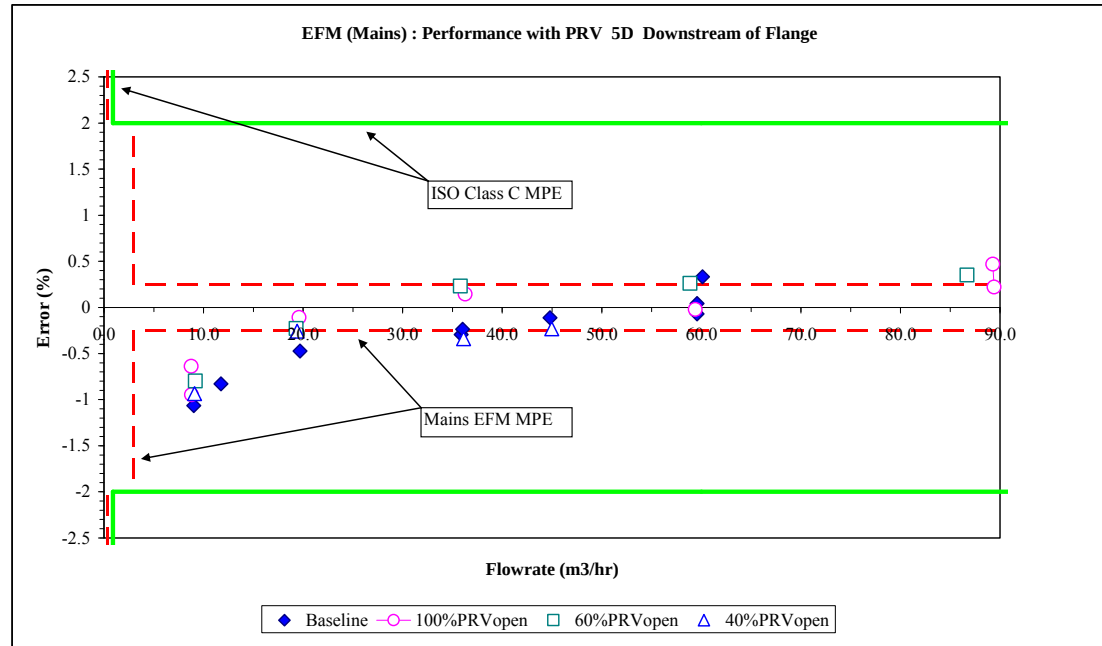


Figure 4.31: EFM (mains): performance with PRV 5D D/S of flange

Whilst the data shows a discernible positive shift associated with the presence of the PRV, the limited number of recorded points means that the result is not statistically significant.

Thus, when compared with the baseline results, placing the PRV 5D downstream of the mains powered EFM cannot be shown to have other than a marginal influence on its performance.

4.8.4 EFM (battery) performance; PRV 5D downstream of flange

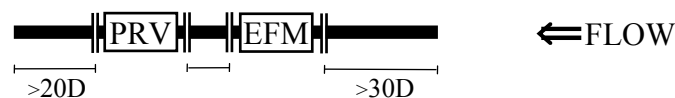


Figure 4.32: Meter test arrangement: - meter horizontal; pipework horizontal; PRV 5D D/S of EFM (battery)

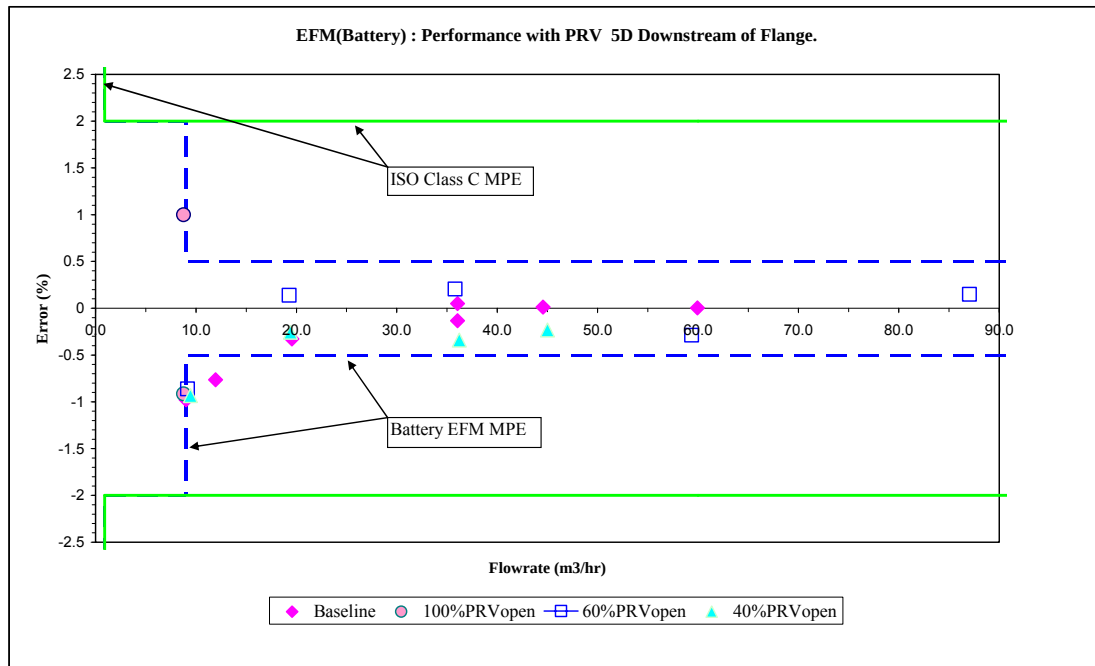


Figure 4.33: EFM (battery): performance with PRV 5D D/S of Flange

The spread of results for the battery powered EFM, fitted with the PRV in line 5D downstream, is similar to that seen for the repeated tests made during the baseline calibration runs. One data point in figure 4.33, at 8.75m³/hr, +1.0%, may be classified as an outlier in that it fails to follow the trend of other results. However, this and all other points remain both within the MPE envelopes claimed by the manufacturer and by the ISO standard.

The conclusion for the battery powered EFM reflects that found for mains powering, namely that placing the PRV 5D downstream cannot be shown to have other than a marginal influence on performance.

4.8.5 Woltmann performance; meter 5D upstream of PRV

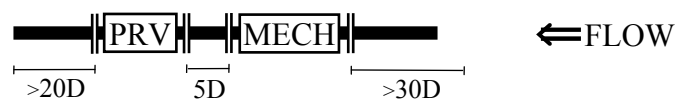


Figure 4.34: Meter test arrangement: - meter horizontal; pipework horizontal; PRV 5D D/S of Woltmann meter

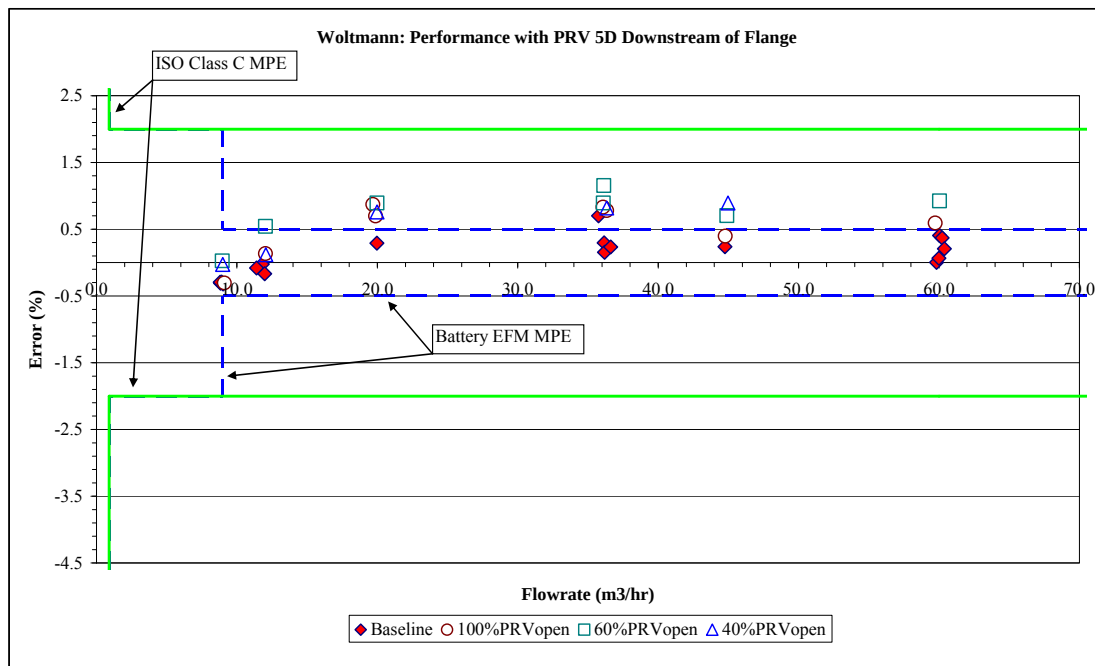


Figure 4.35: Woltmann: performance with PRV 5D D/S of flange

The presence of the PRV at 5D downstream of the mechanical meter created a small positive bias of around 0.3 % - 0.4 %. However, the spread for repeated tests achieved during the baseline tests was in the range 0.4 % to 0.5 %, masking any meaningful statistical interpretation of this small bias. Conformance with the ISO MPE limits is maintained.

4.8.6 EFM (mains): performance with PRV bolted onto downstream flange

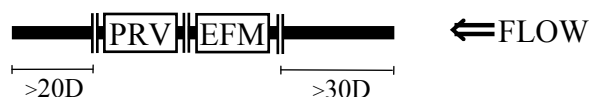


Figure 4.36: Meter test arrangement: - meter horizontal; pipework horizontal; PRV bolted to flange of EFM (mains)

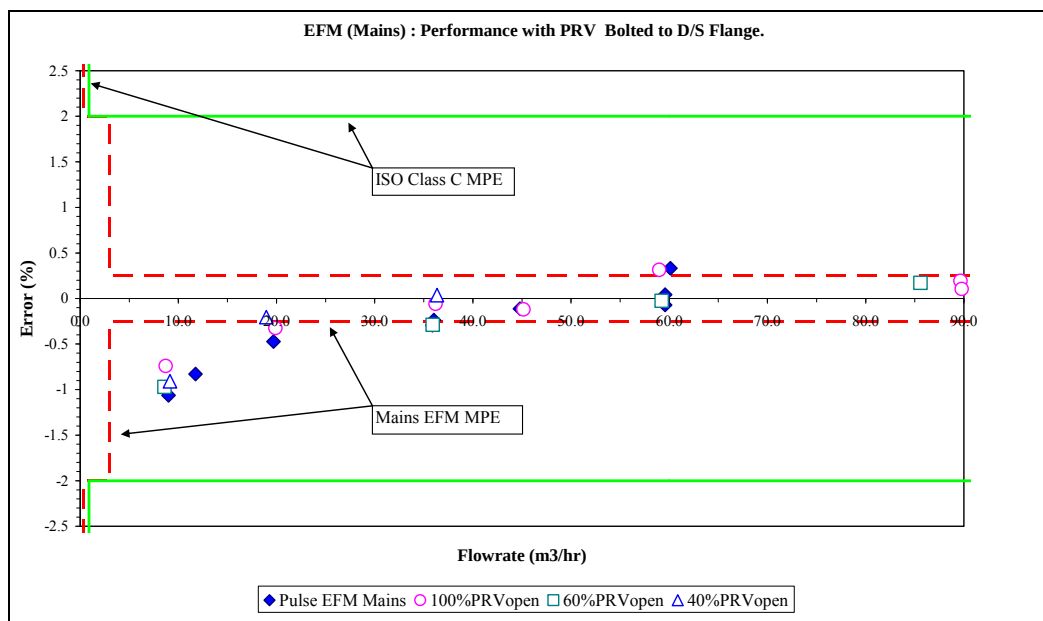


Figure 4.37: EFM (mains) performance with PRV bolted onto D/S flange

Comparison with the EFM performance, achieved when the PRV was spaced 5D downstream, indicates that the results with the PRV bolted directly onto the flange of the meter are similar. In objective terms the EFM displayed conformity with the ISO MPE limits but failed to meet the tighter EFM(mains) MPE stated by the manufacturer.

4.8.7 EFM (battery): performance with PRV bolted onto downstream flange

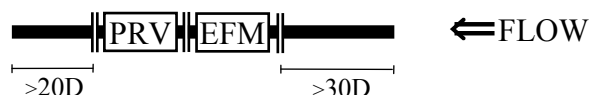


Figure 4.38: Meter test arrangement: - meter horizontal; pipework horizontal; PRV bolted to flange of EFM (battery)

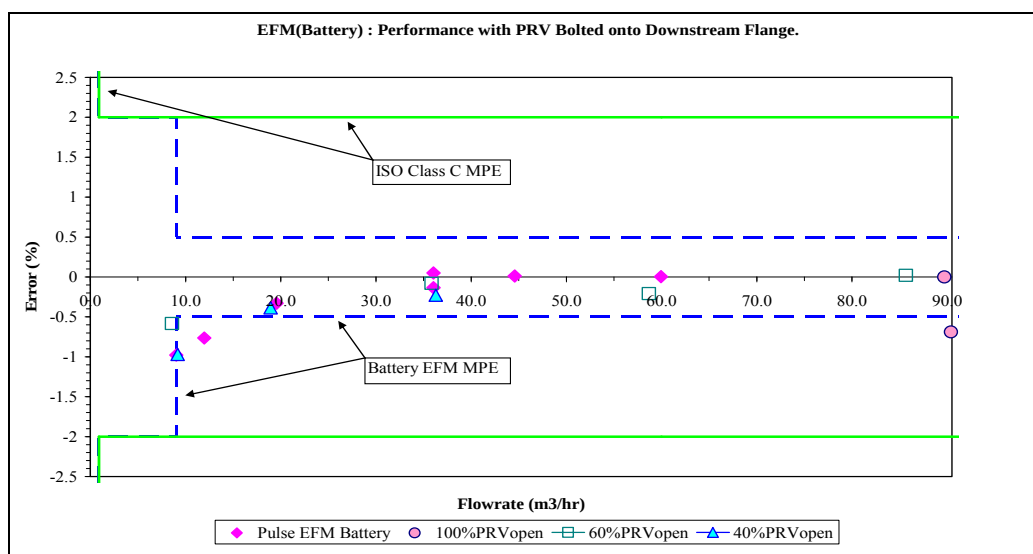


Figure 4.39: EFM (battery) performance with PRV bolted onto D/S flange

Bolting the battery powered meter to the PRV gave marginally smaller errors than those achieved when the PRV was spaced 5D downstream. However, set within the experimental context set by the spread of the repeated results of the baseline tests, bolting the EFM to the PRV has no significant effect.

In summary, when battery powered and bolted to the PRV the EFM met both the ISO MPE and the tighter manufacturer EFM (battery) limits. This contrasts with mains powered MPE operation where the manufacturer MPE was exceeded.

4.8.8 Woltmann performance with PRV bolted onto downstream flange

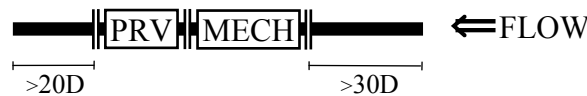


Figure 4.40: Meter test arrangement: - meter horizontal; pipework horizontal; PRV bolted to flange of Woltmann meter

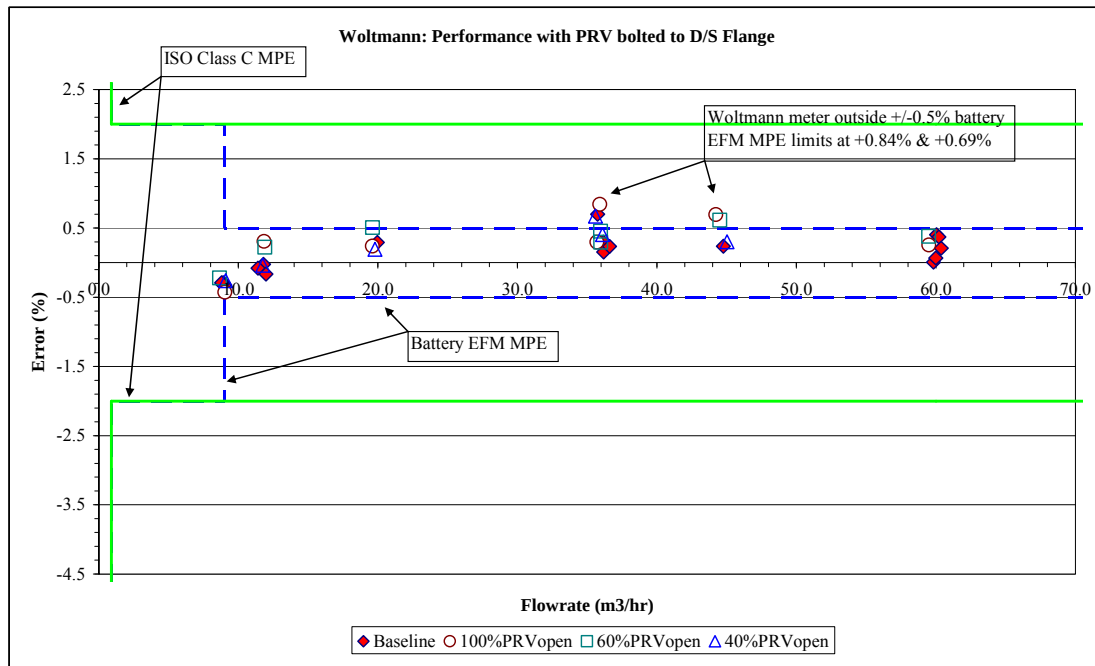


Figure 4.41: Woltmann: performance with PRV bolted onto D/S flange

Compared to separating the two components by 5D, bolting the Woltmann meter to the PRV showed a small reduction in the spread of errors of the order of 0.2 %, lowering the centre part of the performance curve. In common with all previous results examining meter performance in proximity to the PRV, the spread of the baseline results limits the scope of conclusions to be drawn from such a small shift.

Conformity to the ISO MPE limits is achieved but the battery powered EFM limits are not met. However, the margin of exceedance, as is indicated in figure 4.41, is small at +0.34% and +0.19% above the 0.5% manufacturer battery EFM MPE limit.

In summary one may conclude that bolting the Woltmann meter directly to the PRV has no significant effect on performance.

4.9 DISCUSSION OF NETWORK METER TESTS

4.9.1 Note on the applicability of the EFM test results

- (A) All of the EFM and Woltmann results were generated from averaged datasets with logging periods ranging between 600 and 1200 seconds. Such integration periods were chosen to collect results, representative of the EFM design, which could be considered statistically sound. This was especially so for the EFM battery mode where the NSE statistics, created from the individual flowrate measurements, were significantly higher than in the mains mode. It is therefore important to recognise that the EFM results, whether in battery or mains mode, reflect a generic characteristic of the particular EFM design where the calibration performance has been determined from data collected over minutes rather than seconds.

Performance data made available by the EFM manufacturer underlines the need to consider the end application of the design evaluated because of the variation in the zero point recorded over the space of several hours. Whilst small, at $\pm 0.15\text{mm/sec}$, short term flow measurements will reflect such zero variation because of the low minimum flow which the battery and mains versions of the EFM can achieve. e.g. at the minimum battery EFM flow the zero short zero variation represents 1.15% of the magnitude of the sensor velocity for that flow.

In its standard programmed mode the battery EFM is matched to the slowly varying flows within distribution networks. The standard mode logs at 15minute average values, with the average derived from sixty, 15second separated, samples. As such the standard battery mode is not appropriate in other application areas e.g. abstraction or booster flows where rapid, intermittent, pumping regimes exist.

- (B) In contrast, for the Woltmann design, measurements of flowrate will always be effectively low pass filtered because of being based on a volume-pulse output train, which is itself deriving from a momentum based sensor. The Woltmann results, as expected, did not therefore show the same variability in recorded data as the EFM, where the flowrate data is derived from a velocity sensing sensor. However, a similar comment to that made concerning the EFM also applies to the mechanical meter: namely that the meter has to be appropriately matched and sized to the application.

4.9.2 Baseline performance against differing specifications

- (A) When both the EFM and Woltmann meters were installed in straight pipework with >50 clear diameters upstream and >30 diameters downstream, all the results were found to lie within the ISO 4064 class C maximum permissible error limits (MPE); subject to the number of points tested. This applied to the EFM both in mains and battery mode. This outcome reflects directly on the limits of $\pm 5\%$, $\pm 2\%$ found in that standard.

- (B) When in the mains mode, the EFM failed to meet the manufacturer's enhanced performance claim, of $\pm 0.25\%$ in the upper zone, with two data points falling outside the MPE limit. However, this failure should be regarded as marginal because of the difficulty in assigning an uncertainty, which adequately expresses the combined influence of the test method and the quality of the data recorded, to individual results.
- (C) When in battery mode, the EFM met the manufacturer's enhanced performance claim of $\pm 0.5\%$ in the upper zone. Nevertheless, the experimental results demonstrated the expected degradation of meter performance when the EFM is operated in battery mode, as compared to mains operation. The Cranfield laboratory testing therefore independently confirmed the manufacturer's claims for the first time.

4.9.3 Influence of typical network installation practice and components: performance obtained when installed in a bypass arrangement

- (A) Test results showed that the EFM performance was within the ISO 4064 class C MPE limits when the meter was subjected to the poor hydraulic conditions generated by the bypass pipework; subject to the number of points tested. With bends at 3.5D upstream and downstream, the meter performance was affected by less than $\pm 0.5\%$. Noticeably, rotation of the complete bypass arrangement away from the horizontal did not add to the size of the measured errors, indicating that for the commonly used "industry standard bypass" arrangement the meter design was unaffected by the disturbed hydraulic conditions which this arrangement induces.

4.9.4 Influence of typical network installation practice and components: performance in proximity to a gate valve (GV)

- (A) Testing showed that the position and state of opening of an upstream GV makes little difference, subject to the number of points tested, to the accuracy of volume indication achievable by the EFM: defined relative to the MPE performance limits set in ISO 4064. This was illustrated by the results recorded from the EFM under the severe hydraulic conditions created when the GV was bolted directly to its downstream flange. With the valve shut by 10 turns out of 14, the EFM performance remained within $\pm 2\%$, thereby achieving compliance with the ISO 4064 class MPE limits; subject to the number of points tested.
- (B) Further observations of the tests which positioned the GV in close proximity to the EFM indicated that, in the fully open position, the GV can generate errors which are of the same order as those seen when the valve is partially shut. This result was not expected. Two suggestions are made by way of explanation. The first relates to the fact that, when fully withdrawn, the design of the GV creates a rectangular void above the round pipe cross section. See figure 4.42. This void space can induce local recirculation of the flow, distorting the profile immediately upstream of the meter and generating flow noise close to the measuring electrodes.

The second explanation relates to the influence which the GV mass will have on both the weight function and virtual current of the meter [38, 39]. Because of the

relative dimensions of the GV and EFM, schematically shown in figure 4.42, the GV will undoubtedly cause distortion of the EFM field.

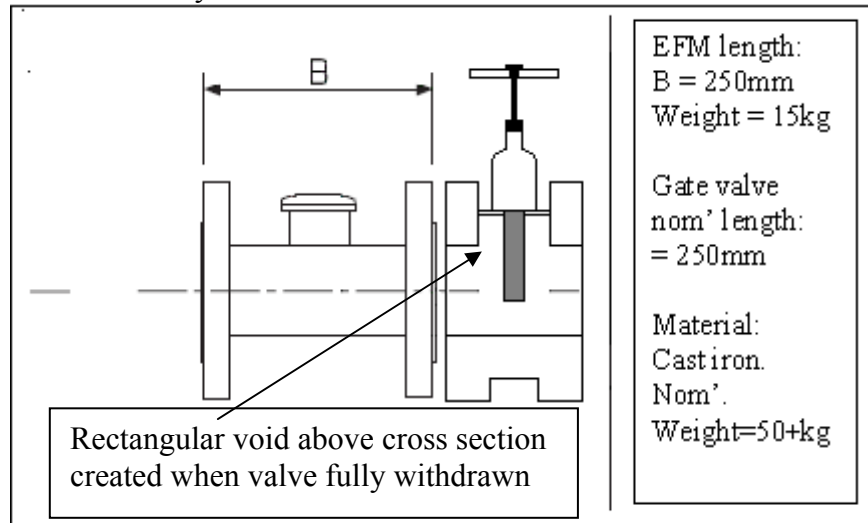


Figure 4.42: Schematic illustration of close coupled EFM sensor and GV

The closeness of the GV is explicitly in direct contradiction of the manufacturer's recommendations. Moreover, it has the capability to shift the EFM's calibration in an undetermined manner as the GV mechanism is moved in and out over the range of its opening. However, the evidence from the laboratory experiments was of noisier, more spread measurements when the valve was fully open, rather than of a measurable shift in the EFM calibration as was speculated.

- (C) When the gate valve was bolted to the flange of the EFM the manufacturer's claimed enhanced MPE limits were not met, either in battery or mains powered modes. This is an important finding as one of the purported advantages of buying the particular EFM design tested for network flow measurement is that of increased accuracy. As the GV tests violated the manufacturer's installation advice this result could have been expected, but what importantly was shown was that even under such poor conditions the ISO 4064 MPE limits were met; subject to the number of points tested. This result has a very practical outcome, allowing simpler, cheaper, less expensive installations to be made without sacrificing accuracy.

4.9.5 Influence of typical network installation practice and components: performance in proximity to a PRV

- (A) Investigation of the effects of locating another common network component, namely a PRV, in close proximity to both an EFM and a commonly used "industry standard" Woltmann meter, demonstrated similar results to that achieved with the combination of EFM and GV. The PRV measurements showed that the effect on the EFM and Woltmann designs was to cause an increase in the magnitude of the volume flowrate error of between +/- 0.4 to +/- 0.6 per cent, relative to the individual baseline performance observed under ideal pipework/hydraulic conditions.

4.9.6 Influence of spacing between meter and gate valve or PRV

- (A) Contrasted to the performance when bolted to the meter flange, the change observed when the GV and the meter, EFM or mechanical, were spaced apart by 5D was small enough that it could not easily be distinguished from the general spread of results observed as part of the experimental method: typically $\pm 0.4\%$ to $\pm 0.6\%$. This has significant practical implications because, without exception, meter manufacturers advise that their designs be spaced away from disturbances, typically by 5D to 10D [60, 61].
- (B) Examining the errors over the range of flows where the GV or PRV was spaced away from the MUT (meter under test), leads to the conclusion that there is no overall advantage to separating the MUT from either network component. Whilst the caveat remains that this conclusion has been demonstrated only for the particular laboratory combination of GV, PRV and EFM/Woltmann designs, the setup and components were carefully chosen to be representative of current water industry practice.
- (C) The test results, subject to the number of points tested, thus form the basis for revising current industry practices. These practices impose additional pipework costs and additional installation constraints by specifying separation of meter and network components, usually by 5D. The laboratory testing has shown this to be unnecessary, subject to the number of points tested, should conformance to either the ISO 4064 or the manufacturer MPE limits remain acceptable. Further work, incorporating additional test points, would however be prudent.

4.9.7 The utility of adopting MPE limits for network meter performance

- (A) Use of an MPE approach when assessing EFM performance, in contrast to adoption of the more traditional, single value, linear meter factor, conferred real practical advantages when assessing the EFM with network components and/or pipework installation conditions. Whether referencing the manufacturer or the ISO 4064 standard MPE limits, the MPE band allows for a spread of results, some created by the measurement technique itself e.g. battery powering, others created by the hydraulic environment to which the meter is subject e.g. proximity to a GV, PRV etc.
- (B) By implication, specifying a given MPE as the determining factor in defining a meter's performance will, de facto, require the user to suitably match that MPE to a discrete application area e.g. a DMA, a major consumer supply, an abstraction source etc.
- (C) In turn, because of the uncertainty bands bounded by the MPE build directly into determining the overall network water balance, the difference between the ISO 4064 MPE and alternatives, such as the EFM manufacturer's MPE's evaluated in the laboratory testing, is one of significance. It underlines the importance of the present laboratory test results, subject to the number of points tested, as a guide to understanding the achievable and appropriate meter performance in network operation.

5 IMPROVING KNOWLEDGE OF PROBE CALIBRATION, PERFORMANCE, LIMITATIONS AND VERIFICATION CAPABILITY

5.1 OBJECTIVE

The aim of the Hams Hall laboratory work which followed that undertaken at Cranfield, was (a) to improve knowledge of the calibration, performance and limitations of the battery EFM insertion probe and (b) using this knowledge to benchmark the level of performance achievable when using such a battery probe for meter verification purposes.

Note: it is the probe variant of the battery EFM which is widely used to verify key regulatory meters, so contributing to the calculation of individual water companies' water balance data. The key regulatory meters are otherwise known as WISPY or water into supply meters.

To achieve these twinned aims work was undertaken in five areas to:

- a) create and then characterise an independent, traceable, probe calibration standard facility; abbreviated to IPTS - insertion probe transfer standard;
- b) use this standard facility to investigate and quantify the uncertainty associated with battery probe calibrations.
- c) use the same facility to examine the changes, post calibration, in probe performance and stability after one year's field use verifying WISPY production meters;
- d) determine the sensitivity of the probe output to angular misalignment and thus to assess the practical importance of this source of error and finally to;
- e) benchmark the performance of the battery EFM probe as a meter verification tool, using the laboratory standard conditions which the above work had defined.

5.2 BACKGROUND TO INSERTION PROBE CALIBRATION AND TESTING

5.2.1 External regulatory reporting

With the creation of company meter verification programmes by the major UK water plc's, the need to be able to qualify field measurements relating to meter performance changed from that of an internal technical issue, to one linked to company performance and external audit. In these circumstances, dependence solely upon the manufacturer's calibration claims provides only limited robustness in regard to data traceability. The pursuit of independent means of checking and calibrating key equipment therefore offered the possibility of increasing the confidence with which regulatory data could be reported.

5.2.2 Independent check of manufacturer data

Initial work in the majority of water plc's where insertion technology was utilised centred on mechanical probes. The most widespread of these was manufactured by Quadrina Ltd. However, the difficulties of maintaining initial levels of technical performance, due to day to day wear and tear, militated against continued use. In

addition, when profiling with this make of probe, the accurate measurement of point velocities together with profile integration software which was restricted to the equal annular area method, introduced practical limitations.

The combination of these concerns encouraged the adoption of EFM battery probes. Two designs were trialled by NEL [33]. The preferred design from ABB had been on the market for some years but was limited by the capability of the transmitter driving it. In response to the developing market a new variant which retained the sensor design but used a battery powered transmitter which was common with the full bore EFM meter was offered.

In theory the calibration performance of this battery EFM insertion probe was an improvement, being set by the enhanced transmitter specification but no information was publically available. Hence the initial impetus to pursue an examination of the battery EFM probe calibration was linked to the need for knowledge of the effect which the transmitter changes had made to the transmitter/probe combination. In parallel the need existed to build up an understanding of the reliability of the manufacturer's own calibration figures.

5.2.3 Need to define baseline performance

A parallel driver concerning data quality and confidence came from the results of site velocity profiling where repeated visits had generated values which varied widely and inconsistently [62]. From such results it was unclear as to whether the scatter on the Environment Agency (EA) meter verification data was either (a) the product of combining the uncertainties associated with site techniques or (b) that the application to which the insertion probe was being introduced, was, in effect, inappropriate due to inherent design limitations.

As a result the ability to be able to benchmark in an independent and controlled environment both probe calibration and probe profiling performance, including known practical difficulties such as probe misalignment with the direction of flow, was needed. Moreover, included within this general requirement was the need to formally assess the uncertainty of probe calibration in order to be able to place probe performance in context with the other sources of error encountered.

5.2.4 Software development needed to improve data acquisition

Work on the performance of the full bore battery EFM calibration in the Cranfield laboratory had highlighted the usefulness of operating with digital data when examining small differences in performance. However, the acquisition of real time flow-rate data required bespoke software to be developed in order to create the same accuracy which could be achieved with a diverter system, allied to a pulse counting register. This software development formed another driver which would build to fulfil the stated aim of creating fully traceable probe calibration records.

5.2.5 Creation of a de facto probe calibration standard facility

Comparison of calibration methods for the battery EFM probe and the mechanical probe showed that the current methods adopted lacked traceability and were specific to the manufacturer's production facilities. A facility was therefore needed to create a de facto

standard against which the calibration, ex factory, of differing equipment could be verified, both initially and then over time. As such, it would demand long term stability and characterisation at a level traceable to national standards.

5.3 VELOCITY PROFILING THEORY RELEVANT TO THE PROBE CALIBRATION TEST REFERENCE PIPEWORK

5.3.1 Factors relevant to the proposed probe calibration standard section

To create a precision calibration facility for the battery EFM insertion probe it was necessary to consider the requirements of the pipework layout, hydraulics and critical factors determining the operation of the calibration process.

Generation of a probe calibration depends upon understanding the way in which the particular probe can be deployed, its characteristic relationship to the conduit velocity, plus a defined and traceable hydraulic section whose velocity profile has been characterised by repeated measurements. It is the latter which initially presents the biggest challenge because of the difficulty in independently demonstrating the validity of the profile.

Investigation of the approach taken by the battery EFM probe manufacturer, ABB, revealed that their approach to calibration was founded simply upon the theoretical calculation of the characteristic of the hydraulic velocity profile; for the size of pipework used to test probes. This approach is surprising because the insertion meter will potentially distort the assumed velocity distribution. However, the general principle, which is to characterise the velocity profile of the test pipework, its cross sectional area and the true bulk velocity is sound. Nevertheless, at the time the manufacturer was unable to demonstrate an independent measurement of the test pipework velocity profile and therefore unable to demonstrate full traceability of the probe calibration in the event of a formal audit, as might be requested by the EA.

5.3.2 Investigations of velocity profile theory to assist the practical measurements

Prior to undertaking practical measurements a review was made of previous investigations and theories developed to describe the form of a velocity profile under conditions of fully developed, turbulent flow. The aim was to select the most appropriate theoretical approach which would best support the interpretation and analysis of the practical laboratory profile measurements.

Unfortunately the definition of what constitutes fully developed conditions varies and is subject to the vagaries of practical pipework layouts. Long straight upstream pipework is a prerequisite and Baker and Tarabad [63] nominated a figure of not less than 60D from a point of disturbances. UK based ABB provides varying advice, with a set of conditions between 10D to 80D, depending upon the types of upstream disturbance. The FLOMIC report [64] similarly details different lengths for different outcomes. Therefore, irrespective of the mathematics, it was clear that the number of clear upstream diameters should simply be as large as the laboratory layout would allow.

An examination of the literature indicated that there have been four major contributors to the basic theory behind velocity distribution in fully turbulent flow, namely Prandtl [65], Nikuradse [66, 67], Pai [68] and Pao [69]. Therefore, as a prelude to the practical work it was considered advisable to review these contributions in order to construct a sound basis for the interpretation of the planned measurements which would then be informed by the theory.

5.3.3 Prandtl's one-seventh Law

For steady, fully developed, turbulent flow in a conduit where the fluid is Newtonian and can be considered as incompressible for practical purpose, Prandtl derived what has become known as the one-seventh power law. It is the simplest equation available to describe the velocity distribution within a circular conduit and is given by:

$$\frac{u}{u_{\max}} = \left(1 - \frac{r}{R}\right)^{1/7} = \left(1 - \frac{2r}{D}\right)^{1/7} \quad (5-1)$$

From this empirical equation, one can observe that $u/u_{\max}$ is a function only of r/R .

This means that, when the flow pattern is turbulent, the shape of the resulting velocity distribution is independent of pipe diameter, flow rate or even fluid. In fact, the reality is more complicated as the value of the power, $1/7$, does not remain constant, decreasing with Reynolds number. Nevertheless, Prandtl's $1/7$ th law remains valid for Reynolds numbers between 4000 and about 100,000 which although useful is limited within the context being examined here where Re may vary far more widely.

Starting with equation 5-1, the one-seventh law is often rewritten as:

$$\frac{u}{u_{\max}} = \left(\frac{2y}{D}\right)^{1/7} \quad y \leq D/2 \quad (5-2)$$

Where, y is the distance from pipe wall.

From this one can obtain the mean velocity for the nominal mean velocity positions, $D/8$ and $7D/8$ as:

$$\frac{u_m}{u_{\max}} = 0.82 \quad (5-3)$$

Next, by integrating the profile over the pipe cross sectional area, one can obtain the volume flow rate, thus:

$$Q = 2\pi \int R u dR \quad (5-4)$$

Substitute into this the value of u from the profile equation (5-1) and one finally obtains the Flow Rate equation:

$$Q = 2\pi \int_0^R R u_{\max} \left(1 - \frac{r}{R}\right)^{1/7} dR = \frac{49}{60} \pi R^2 u_{\max} \quad (5-5)$$

5.3.4 Nikuradse equations

In response to the Reynolds number limitation, Nikuradse developed a different approach for velocity profiling which aimed to overcome Prandtl's restriction in

Reynolds number range. Using experimental results, Nikuradse started with the original $1/7^{\text{th}}$ equation and modified the value of the power value. The relationship fits the following law linking the ratio between u/u_{max} and the constant m .

$$\frac{u_m}{u_{\text{max}}} = \left(1 - \frac{r}{R}\right)^{1/m} \quad (5-6)$$

Integrating this then yields:

$$\frac{u_m}{u_{\text{max}}} = \frac{2m^2}{(m+1)(2m+1)} \quad (5-7)$$

Whilst the value of “ m ” is subject to interpretation within the literature, the most frequently referenced approximation comes from Miller [70] in the form of the equation:

$$m = 1.66 \log \text{Re} \quad (5-8)$$

However, an alternative numerical list, relating Reynolds number to “ m ”, is given by Maclean [64] in Table B2 of FLOMIC report number nine. Please note that the table contains a typing error for the Reynolds number equivalent to “ m ” equals seven, where 10^6 should read 10^5 . Unfortunately, whilst improving on Prandtl, the Nikuradse equation fails to generate both accurate centre line and near wall data, prompting further developments.

5.3.5 Pai equation

Pai (1953) developed a non power law equation which took into account the relative roughness of the pipe wall and hence improved on the near wall and general velocity profile. This was a significant improvement and could be easily applied to differing practical situations.

The Pai equation may be written as:

$$u_m = \frac{u_{\text{max}}}{\left(1 + 1.44\sqrt{f_f}\right)} \quad (5-9)$$

where u_m = average pipe velocity

f_f = pipe friction factor

For point velocities, this can be expressed as:

$$u = \left[1 + \frac{s-n}{n-1} \left(\frac{r}{R}\right)^2 + \frac{1-s}{n-1} \left(\frac{r}{R}\right)^{2n}\right] u_{\text{max}} \quad (5-10)$$

where

$$s = \frac{f_f \text{Re}}{32 + 46.08\sqrt{f_f}}$$

and

$$n = \frac{2 - f_f \text{ Re}/32}{1.44\sqrt{f_f - 1}}$$

Thus, because of the general nature of the Pai equation, the decision was made to use it to initially assist in interpreting the velocity profile measurements made in the Hams Hall laboratory. The details of how the test section profile was measured are given in the following sections.

5.4 CHARACTERISATION OF THE VELOCITY PROFILE OF THE PROBE CALIBRATION TEST REFERENCE PIPEWORK

One of the identified tasks for the Hams Hall laboratory work was to improve knowledge of the calibration, performance and limitations of the insertion variant of the battery EFM. This required the creation and characterisation of an independent, traceable, probe calibration standard facility. The following section(s) describe how this was achieved.

5.4.1 Pipework decisions

To create a reference section in which to mount the insertion probes undergoing calibration, a variety of pipework ranging from 150mm up to 500mm was available in the laboratory. However, the decision of which pipework to choose was instructed by examining the distribution of meter sizes within the population of WISPY meters installed within Severn Trent Water [71]. Here the most common sizes were found to lie between 250 and 400mm.

NOTE: Direction flow - from gate valve to EFM Master Meter (MM)

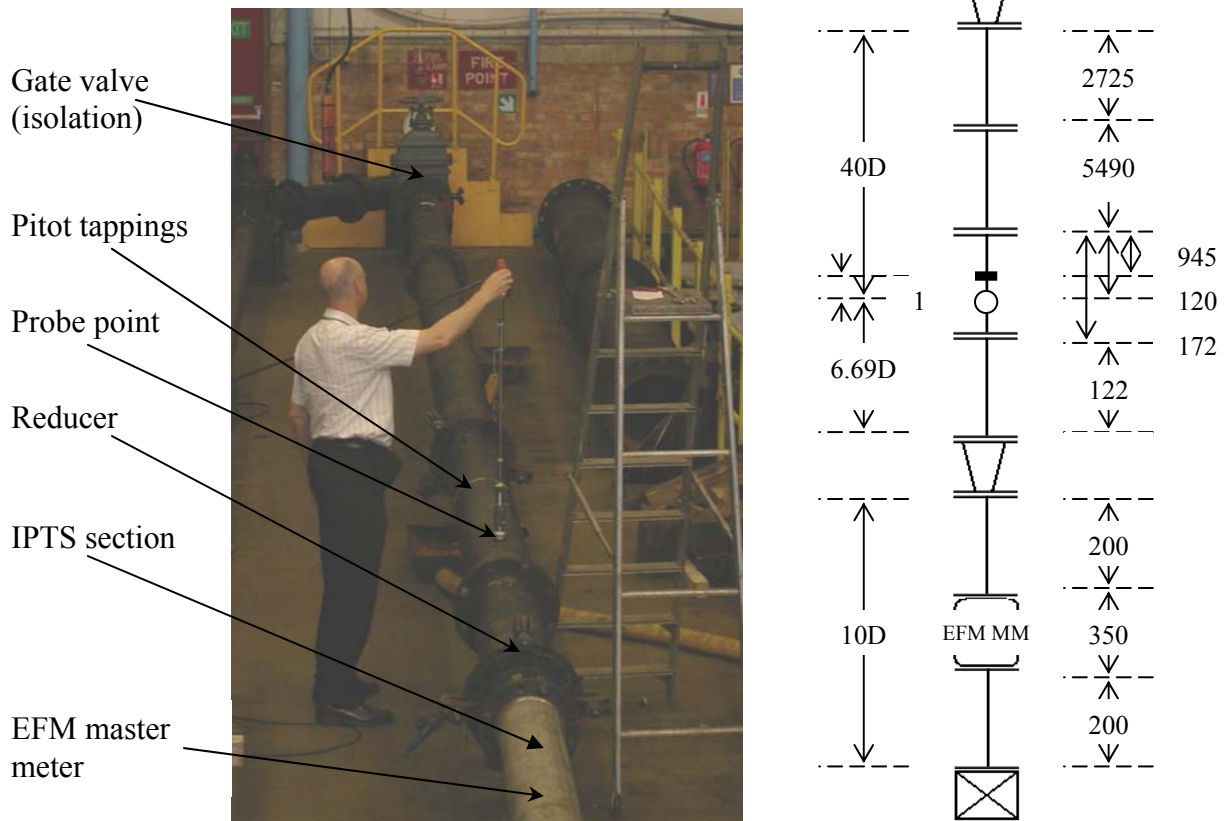


Figure 5.1: Illustration and dimensions for the probe calibration test section

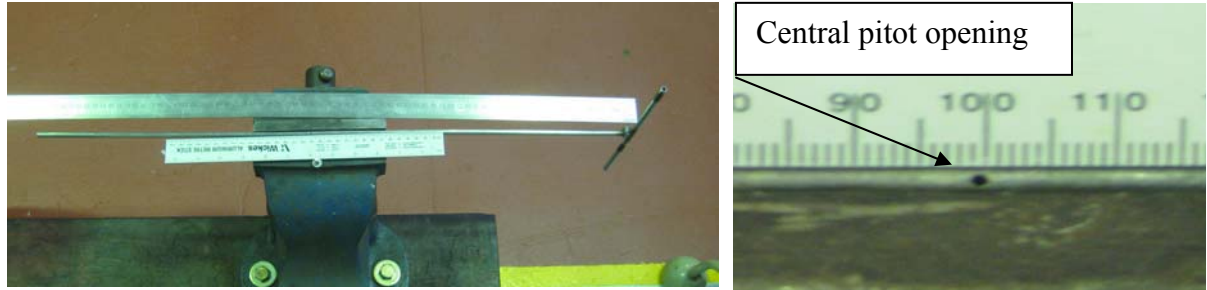
As a result pipework of nominal 260mm (10") bore was selected from that available, there being enough lengths to provide a full run of the Hams Hall laboratory such that 40 diameters (13m) of clear pipe were available upstream of the nominal test point, and 6.7 diameter (1.7m) clear downstream, to where the pipework reduced.

In the field, the vast majority of installations are accessed through a standard 2" gate value. However, in the laboratory, this was deemed likely to create an unwanted physical impediment to accurate measurement of the inserted length. As an alternative a stainless boss was welded onto the top of the pipe and jig drilled and tapped to provide a direct mounting. This had the added advantage of keeping the point of suspension for the probe shaft as close to the crown of the pipe as possible, and so minimising vibration.

The choice of pipework was thus essentially a pragmatic one determined by availability. Nevertheless, it was judged to be technically reasonable (a) because of the upstream and downstream hydraulics and (b) because of the relatively large pipe cross sectional area, compared to the smaller area presented by a probe when inserted into the pipe i.e. the so called "blockage factor".

5.4.2 Details of the beam pitot used for profiling the reference line

The method adopted to define the test reference line velocity profile was based upon use of a specially constructed, 690mm x 230mm, T shaped, stainless steel, 6mm outside diameter, beam pitot. This is shown in figures 5.2 and 5.3.



Figures 5.2 and 5.3: Details of Beam Pitot Tube Assembly Used For Traversing

The principle of application is to indirectly derive point velocity within the bulk pipe flow from measurement of the differential pressure between the beam pitot opening and the bulk pipeline pressure. Whilst technically of lower potential accuracy than alternative laser doppler methods the beam pitot had the advantage of offering simple measurement of pipe flow velocity which can similarly be traced to SI units. In the case of the Hams Hall work the traceability was provided by use of a UKAS calibrated differential pressure transducer.

Figures 5.4, 5.5 and 5.6 show the reference section tapping points, the detail of the beam pitot end sealing arrangements and an illustration of the beam in place on the downstream pipework of the smaller diameter insertion probe transfer standard (IPTS) pipework; not the reference section pipework.

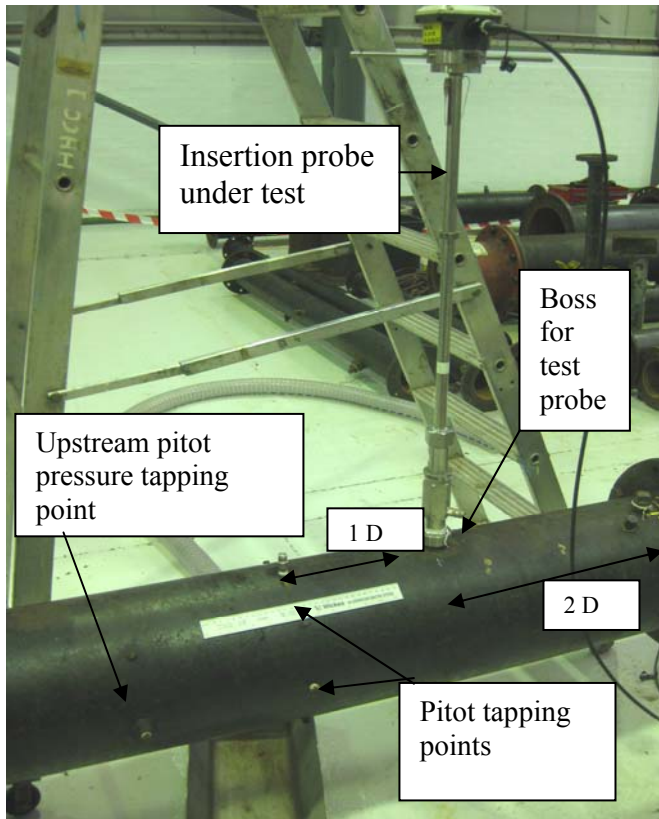


Figure 5.4: Reference section tappings

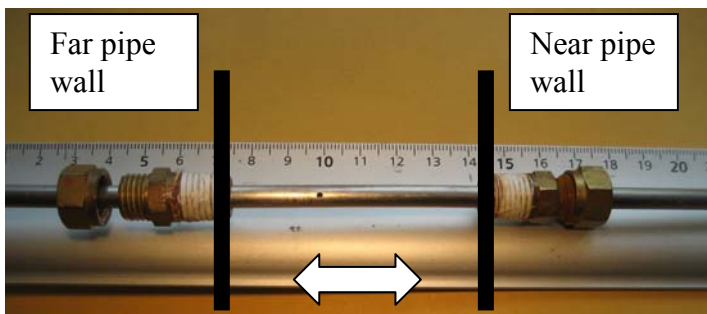


Figure 5.5: Detail of beam pitot end sealing arrangement



Figure 5.6: Beam pitot end installed through IPTS tapping points

Deployment of the beam pitot requires that the 6mm tube is inserted across the diameter of the test reference section diameter, through the opposed pitot tapping points made in the wall of the reference section. It is then moved incrementally from the near side pipe wall to the far side pipe wall, stopping at allocated points. At each point the differential

pressure difference between the pitot opening and the separate upstream tapping made in the pipewall is taken.

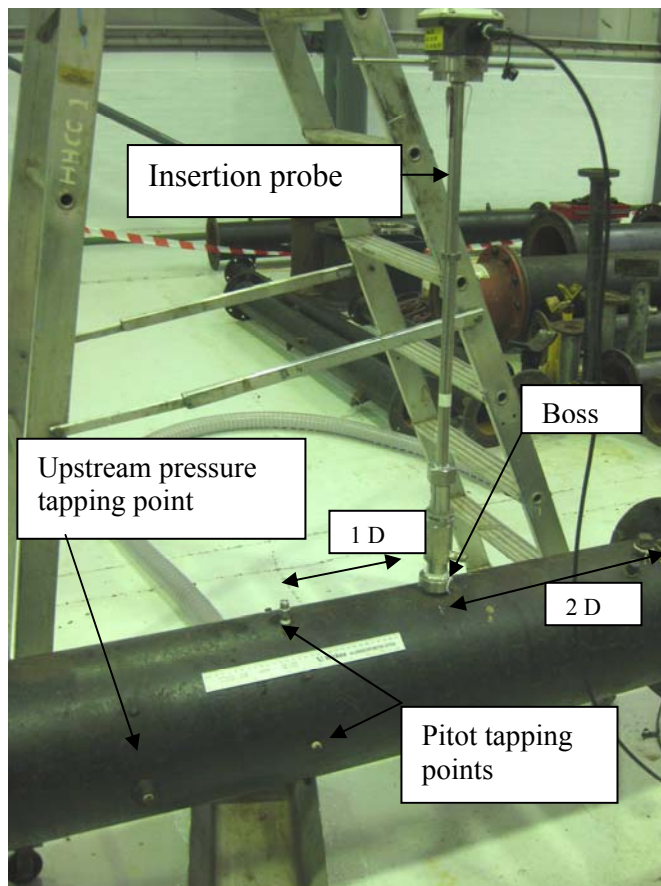


Figure 5.7: Detail of reference pipework tapplings

In the work reference was made to BS 1042/ISO 3354 [35], both for guidance in regard to selection of the position of the profile points and for details of the methods of cubics.

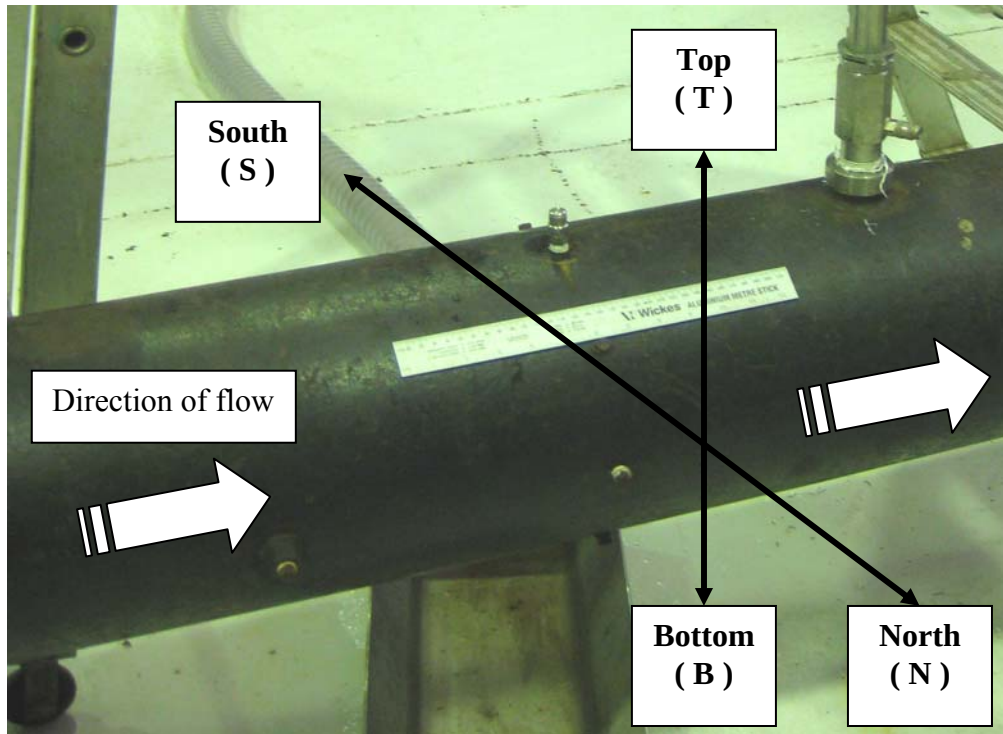


Figure 5.8: Illustration of Hams Hall velocity profile traversing nomenclature

5.4.3 Results of the 1997 beam pitot profile and confidence check

The first sets of velocity profile measurements for the reference section, using the beam pitot, were made in 1997. Both the vertical and horizontal axes were profiled with 17 points per traverse. The horizontal results were designated as “N-S”, north to south, describing the direction of the incremental measurements; the vertical results were designated “T-B”, top to bottom.

The flowrates used for the profile determination were 65.5 l/sec; 150 l/sec and 200 l/sec. These flows were selected against a background of field surveys[72] and were typical of the higher end of the industry range of values. Respectively they individually represent bulk pipe velocities within the 260mm pipe of nominally 1.2, 2.8 and 3.6 m/sec. Line pressure varied between 5.5 psi and 43 psi, depending on whether one, two or three pumps were in circuit to achieve the maximum flow.

Table 5.1 provides a summary of the results.

August 11-14th 1997		Horizontal Traverse Results for Varying Flowrates			
Cubics File Reference	65_5NS46	150NS43	150NS5_5	200NS40	"NS" = North to South
Measured flowrate m3/hr	235.617	546.443	540.635	718.386	(i.e. across the pipe)
Cubics flowrate m3/hr	230.8903	534.985	528.6776	702.0364	Mean Profile Factor
Velocity (using cubics)	1.208	2.799	2.766	3.673	Horizontal
Profile factor	0.8391	0.8413	0.8325	0.8398	0.8382
Scaling (measured/cubics)	1.0205	1.0214	1.0226	1.0233	
Line Pressure (psi)	46	43	55	40	
August 11-14th 1997		Vertical Traverse Results for Varying Flowrates			
Cubics File Reference	65 5TB46	150TB43	150TB5_5	200TB40	"TB" = Top to Bottom
Measured flowrate m3/hr	236.034	545.636	542.755	717.643	(i.e. Vertically)
Cubics flowrate m3/hr	228.0789	528.6776	533.4559	697.0669	Mean Profile Factor
Velocity (using cubics)	1.198	2.766	2.791	3.647	Vertical
Profile factor	0.8306	0.8325	0.8412	0.8357	0.8350
Scaling (measured/cubics)	1.0308	1.0321	1.10174	1.0295	
Line Pressure (psi)	46	43	5.5	40	
Mean value of Horizontal and Vertical Profiles					0.8366

Table 5.1: 1997 Determination of the Hams Hall260 reference test section velocity profile

The results of all the pitot measurements are displayed in figure 5.9, together with the predicted profile lines created by the Pai equation.

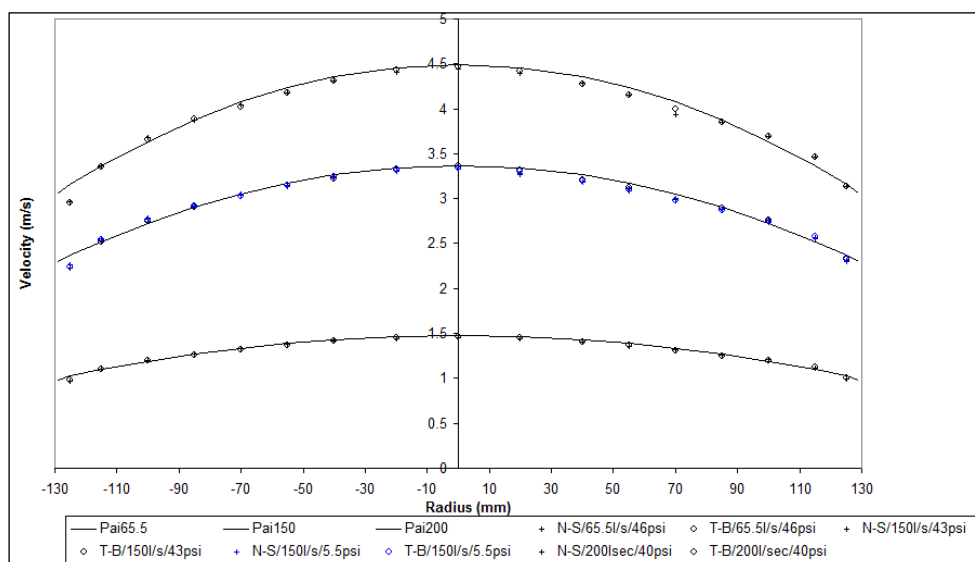


Figure 5.9: 1997 velocity profiles in Hams Hall 260mm diameter pipe

As can be seen the fit is reasonable and gave confidence in the general beam pitot method of independently measuring the velocity profile.

Finally, the relationship between the Reynolds number and the averaged profile factor, F_p , was examined. F_p being defined as the ratio between the mean pipe velocity and the centre line velocity. Figure 5.10 plots F_p against Re .

Please note that the horizontal scale for Reynolds number requires a multiplier of 1000 e.g. the horizontal graph axis maximum is 1000,000 and that the line pressure at the lowest Re was 46psi and that for the highest Re values, 40psi.

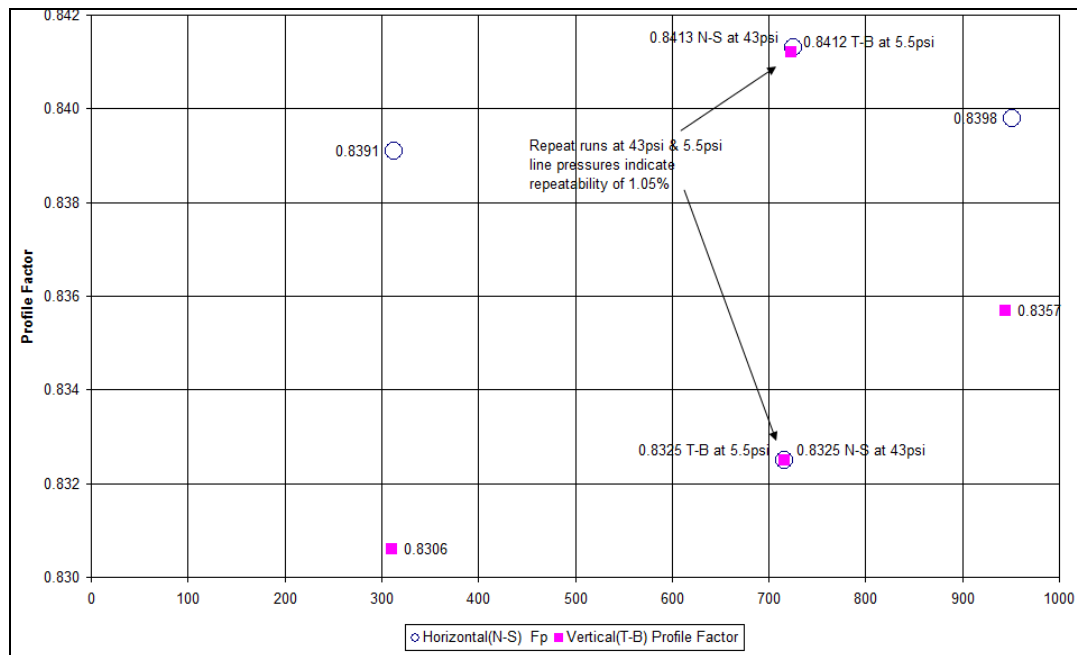


Figure 5.10: 1997 profile factors against Reynolds no.

The point highlighted by figure 5.10 concerns the repeated runs at different line pressures. For both vertical and horizontal sets of measurements the change in profile factor, when varying line pressure, was 1.05%. In detail, F_p for the horizontal plane decreased from 0.8413 to 0.8325, whilst F_p in the vertical plane increased from 0.8325 to 0.8412. When the horizontal and vertical figures are averaged F_p was found to have remained unchanged, despite the changes in pressure.

One may conclude that varying the line pressure whilst nominally maintaining the same flowrate results in no net alteration to the average of the profile factor with a measured repeatability of 1.05%. As a means of assessing the beam pitot method of determining profile factor these results illustrate the measure of confidence, which may reasonably be attributed to the experimental method.

5.4.4 Application of the Pai equation curve to 1997 profile results

As described earlier it had been decided to use the Pai equation to initially assess the results of the laboratory profile. However, before one can plot the Pai curves, it is necessary to determine the roughness for the test pipework. To establish the roughness a large number of measurements, >60, were made on different parts of the inner surface of the reference section using a rotary piston gauge mounted on a stand. These measurements allowed variations in roughness around the pipe to be assessed, but to no better than $\pm 0.05\text{mm}$. A smaller number of alternative measurements were taken

using an internal micrometer but although in theory one should have been able to generate improved data, the practicalities of accurate alignment and exact location across the pipe diameter made the exercise one where the level of confidence diminished over time.

The resultant averaged roughness results, which are not tabulated, gave a mean for the maximum to minimum of close to 0.20mm. Nevertheless, statistically this result must be regarded as only approximate because of the simplistic method of the roughness measurement technique.

As an aid to understanding the sensitivity of the Pai equation profile to surface roughness figure 5.11 was produced. This uses the best estimate for the internal diameter of the reference section, 260.3mm and a water temperature of 25° Celsius, typical of that during testing, so generating a value of $Re = 1096\ 000$.

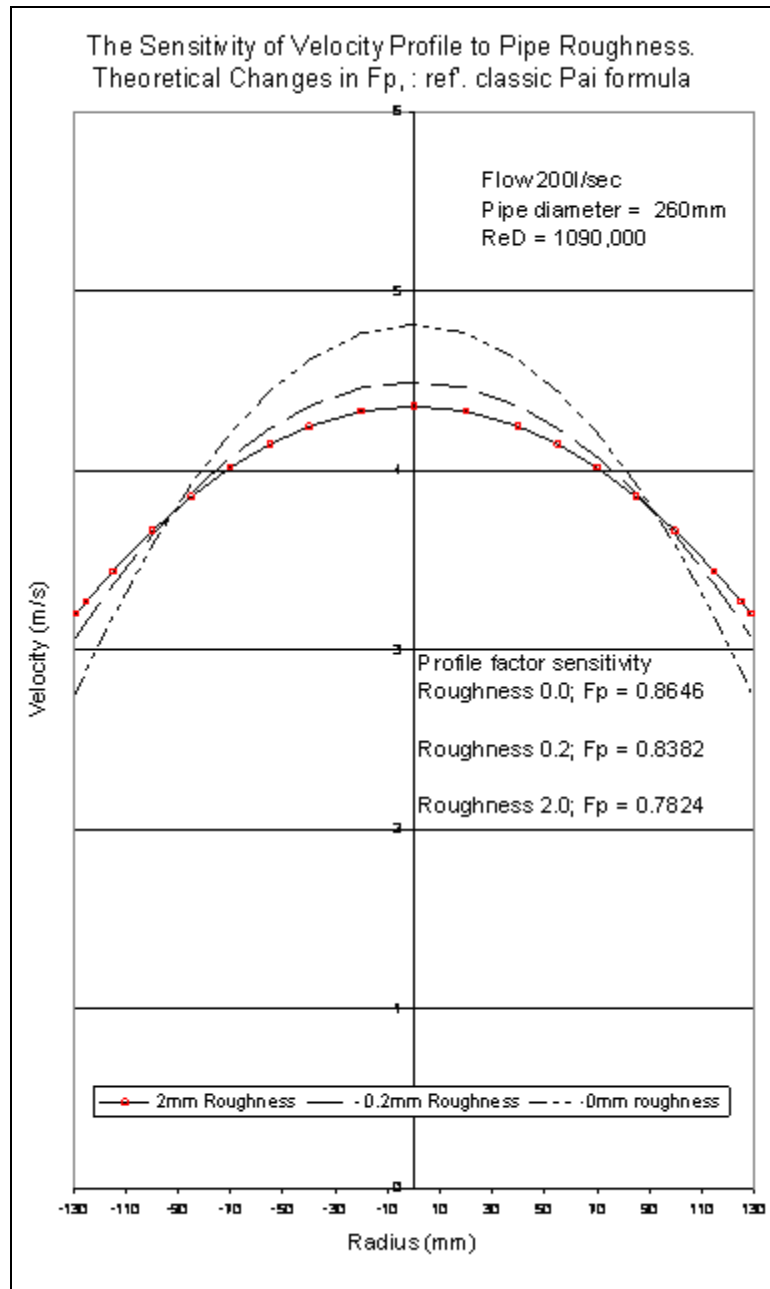


Figure 5.11: Sensitivity of the Pai equation profile to pipe roughness.

Inputting 0.2mm as the pipe roughness, the Pai equation generates a value of F_p of 0.8382. When compared with the averaged horizontal and vertical F_p derived from the pitot data of 0.8366, the difference between Pai and practice is -0.2%.

When calculated for a smooth pipe the value of F_p becomes 0.8646. This is +3.15% larger than the value calculate for a roughness of 0.2mm. The probability is therefore that the actual pipe roughness is slightly greater than 0.2mm but that 0.2mm represents the best estimate of roughness.

Overall, the result provides additional confidence in the practical, pitot based measurements but, as figure 5.9 shows, maintaining a long term, stable, pipe wall roughness is key to ensuring that the profile can be routinely replicated.

5.4.5 Use of the developed reference pipework to check the manufacturer's Probe calibration

Following the Hams Hall reference pipework profile determination a batch of 18 battery EFM insertion probe meters was calibrated; directly after purchase from the manufacturer. The results were unexpected with significant differences between the mean meter factor stated by the manufacturer and that measured using the reference section. Two probes registered errors in excess of 10 percent with the remaining 16 showing an average meter factor of +5.9% greater the Hams Hall value.

The calibration procedure adopted at Hams Hall is given in Appendix 10 but the key point applying to both sets of calibrations was that, with the exception of the profile factor, the same manufacturer defined probe-setup figures were used. Hence it was logical to conclude that it was the profile factor which was central to the observed calibration differences.

Further work revealed that the manufacturer had not undertaken any independent check of the profile used in the factory calibration but had determined the profile of their section using a general textbook value. When applied to the reference pipework at Hams Hall this approach would have given a figure for F_p of 0.852, +1.84% higher than the actual measured figure.

After internal work the manufacturer corrected his original factory profile by 3.5%. Repeated testing of the resubmitted batch of probes then returned a mean error against Hams Hall of +1.43%. This margin of error was judged by the manufacturer to be within their acceptable tolerance limits.

The exercise in validating the manufacturer's probes provided a demonstration of the utility of creating an independent and traceable calibration facility, as well as confirming the general accuracy of the reference section profile factor.

5.4.6 2006 update to the reference section beam pitot profile

Following the 1997 work spot check profiles were mounted annually but it was not until 2006 that the pipe profile was repeated using the beam pitot. Between the two dates the reference pipework had remained unaltered and had been bolted in the same sequence, with the same flanges placed together, when being used during approximately ten sets of insertion probe calibrations i.e. once a year.

Figure 5.12 which shows the 2006 profile superimposed on the 1997 data. There are two procedural differences: (1) the profile at 200l/sec was omitted (2) only 13 points were taken during traversing, not 17 as in 1997. This latter change was made in conjunction with an alteration to the velocity sampling positions across the developed profile. By removing points crowded about the centre line it was possible to save time without adversely degrading the overall profile assessment.

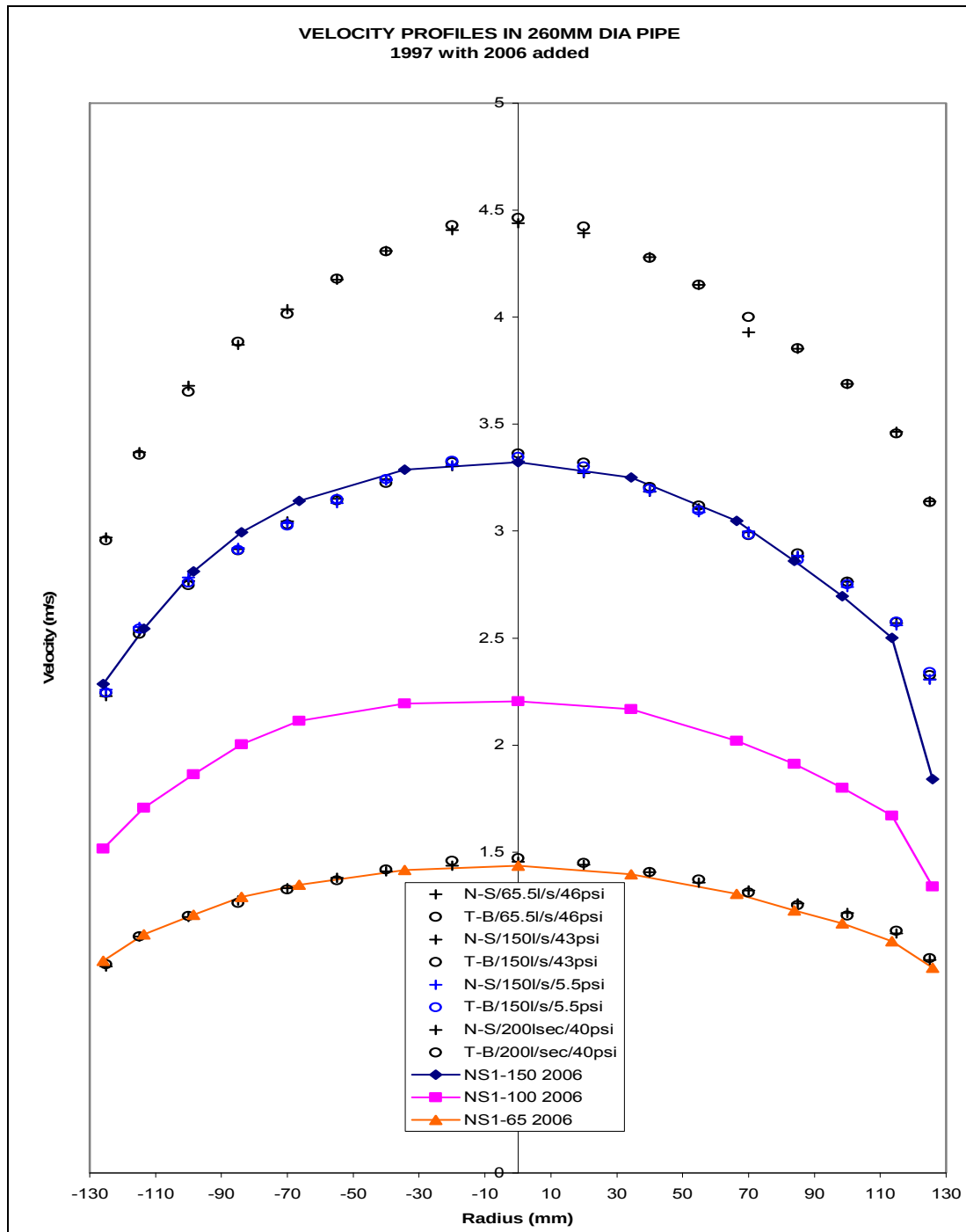


Figure 5.12: Velocity profiles in 260mm dia' pipe 1997 with 2006 added

Table 5.2 summarises the 2006 data and adds both the comparable 1997 results for the same reference section profiled using a battery insertion probe. The probe results utilised the AutoProfile software (described later in the thesis) to both measure the raw point velocity and to output the calculated profile factor. Unlike the beam pitot method the insertion probe derived F_p has to incorporate additional uncertainties, such as that for the probe insertion, or blockage factor, a value which is defined by the manufacturer.

Table 5.2 shows that the mean Dec06/Jan07 probe derived Fp was +0.45% greater than the 1997 beam pitot result but was -0.6% below the 2006 pitot value. This Dec06/Jan07 AutoProfile result thus indicates the level of performance which can be expected under laboratory conditions when measuring Fp using a battery insertion EFM, vis-à-vis the beam pitot reference method.

Date	Dec06/Jan07 Beam Pitot Results					Profile Factor - Vmean/Vcl	2006 profile % diff rel to 1997
	Flow rate (l/s)	65	100	150			
2006	Horizontal - NS (North-South)	0.8530	0.8550	0.8470		0.8517	1.7%
2006	Vertical - TB (Top-Bottom)	0.8490	0.8450	0.8420		0.8453	1.3%
		Beam pitot average 2006 tests =				0.8485	1.4%
							above 1997
	August 1997 Beam Pitot Profile Results						
Aug-97	Horizontal - NS (North-South)	0.8391	0.8325	0.8413		0.8376	
Aug-97	Vertical - TB (Top-Bottom)	0.8306	0.8412	0.8325		0.8348	
		Beam pitot average 1997 tests =				0.8366	
	Dec06/Jan07 AutoProfile Battery EFM Profile						
	Flow rate (l/s)	65	100	150			
	Vertical - TB (Top-Bottom)	0.8420	0.8370	0.8420			
		AutoProfile average 2006 tests =				0.8403	0.45%
							above 1997

Table 5.2: Comparison of all Hams Hall test section profile results

In contrast the 2006 beam pitot profile, when averaged across both axes, was +1.4% higher than that in 1997, with the horizontal traverse being +1.7% and the vertical +1.3%.

Within the limits of uncertainty, which are developed later in the chapter, this was viewed as an acceptable result.

5.5 DEVELOPMENT OF THE I.P.T.S AND PRECISION DATA ACQUISITION TOOLS

5.5.1 Data collection needs

In approaching the technical issues associated with probe calibration a marked difference was noted between the data acquisition methods applied in the laboratory and field environments. This was important because the regulatory testing, undertaken in the field, did not apply the same standards as that in the laboratory, so producing datasets of different quality.

In the laboratory, flowrate data and error determinations were based upon high speed flowrate pulse counting and traceable standards, whilst in the field, volume pulse dataloggers, operating at low speed were standard and little or no regard was paid to traceability. A method was required which could both deliver traceable results and

which offered the opportunity to link laboratory and field results through standardised data recording.

In the Cranfield experiments on full bore meters the use of digital data, accessed through the RS232 port of the EFM transmitter, had proved beneficial in assuring data quality and facilitating data analysis. However, the transmitter fitted to the battery EFM design limited the maximum pulse output to 50Hz. This severely restricted the resolution of flowrate information due to high turn-down experienced by a typical EFM in the field.

Unlike Cranfield, the use of Hyperterminal at Hams Hall was impractical because of the length of time to set-up individual runs; which had to be followed by yet more time to transfer the data into a suitable format for analysis. A new method for collecting digital data was needed. In addition, to be able to offer the same features whether operating in the laboratory or field environment required that the software provide the operator with statistical analysis of the recorded data. This would allow the data collection to be independent of the specific laboratory infrastructure.

A target to try to use digital data collection to reduce the random uncertainty by a factor of two provided a second reason to move away from pulse counting to a fully digital method; but required the start-stop timing of data records to be handled automatically.

Generically, the advantage of avoiding pulse counting lay in obviating the low pass filtering which this method incurs. It also allows direct access of the direct measurements from the (digital) transmitters, without having to work through an interposed digital to analogue convertor. Allied to this, the archiving of data, for subsequent traceable analysis is made easier.

5.5.2 Development of the IPTS design

Experience with full bore meters exhibiting high turn down had shown the difficulties of running the Hams Hall gravimetric system at low flows. With such flows, the time for each divert into the reference tank becomes long, up to an hour or more. The extended time is needed in order to reach the minimum quantity specified by UKAS - to achieve the laboratory's 0.1% stated uncertainty.

A master meter alternative was therefore proposed to avoid such problems. Whilst retaining the traceability, the uncertainty would be altered but could easily be incorporated into the master meter performance statement. With the implicit adoption of time series digital data use of a master meter could also allow the recording software to manage the calibration run schedule, but predicated on the number of samples to be logged rather than the elapsed time.

The foregoing thus established the need for an integrated pipework section incorporating the master meter and the probe calibration point; the IPTS. Size was then dictated by the need to provide operation within the electromagnetic master meter's optimum accuracy range, as well as ensuring that the physical size of the transfer section would allow practical transport within the lab and to external facilities. 200mm was selected. Unlike the existing calibration set-up where the probe was only upstream

of the gravimetric tank, with the IPTS proposal the probe would be downstream of the master meter. Operationally, the opportunity to use the 260mm probe location also existed, offering the possibility of being able to test two probes at a time.

Figure 5.13 and figure 5.14 show the construction of the IPTS assembly. Made from 200mm diameter stainless steel tube it comprises three elements, an upstream length of 2000mm, 10 diameters; the EFM master meter and the downstream section with four tapping points arranged in two orthogonal, symmetric pairs. The master meter is manufactured by ABB and is a commercial design with separate, remote transmitter capable of providing pulse, analogue and RS232 based digital signal outputs.



Figure 5.13: IPTS individual components



Figure 5.14: IPTS components assembled

The design of the tapping points was constrained by the thickness of the tube wall thickness, being too thin to weld a standard boss onto directly. The compromise adopted was therefore to weld tube based extensions onto the main body. The detail of the internal pipe wall is shown in figure 5.15 where the ends of the four plastic blocking pieces can be seen flush with the pipe and figure 5.16 shows the complete assembly mounted in position in the laboratory.



Figure 5.15: IPTS internal tapping detail



Figure 5.16: IPTS installed in Hams Hall laboratory

5.5.3 Development of probe positional encoder

In all documented and practical work, whether laboratory or field based, including the manufacturer's factory calibration method, positioning of the insertion probe within the pipe had been accomplished by measurement with a hand held tape. The exercise of profiling with the beam pitot had taught that positional accuracy was essential to delivering repeatability and that repeatability underlines the level of performance and confidence which can be ascribed to the measurements. Moreover, setting probe

position using a tape is a two person task, one person controlling the movement of the probe until it is at the right point, the other holding the tape and calling the distance. With only one person available to undertake experiments, a secondary driver for improvement was the ability to set up and conduct a profile single-handedly.



Figure 5.17 shows the positional encoder developed to improve both probe positional accuracy and allow one person operation. The device consists of a battery powered shaft encoder, allied to a display and counter. The resolution of the encoder is 0.1mm. but with an assessed accuracy of 0.3mm, as determined by a series of experiments using a standard, traceable steel rule and a mounting block.

Mounting of the positional encoder was simple with the device being temporarily secured to the top of the probe housing in place of the standard top plate; using either the existing plate location holes, or optionally, being held down using crossed elastic bands.

Figure 5.17: Probe positional encoder

The operator then attached the end of the extending wire attached to the internal encoder mechanism to the probe, using the outside safety lock bracket. The probe was then moved to the bottom of the pipe and the encoder display electronically zeroed. Once the zero had been set the probe could be single-handedly pulled out of the pipe with the exact distance moved being indicated on the encoder display. This readout allowed the operator to accurately set the probe position relative to the bottom of the pipe, as dictated by the profiling method. Once positioned at the planned distance the operator can tighten the probe shaft locknut, recheck that the distance has not moved and proceed in the knowledge that the insertion probe is precisely located to better than 0.3mm.

A long term check, made after five years of operation, confirmed that the probe could be moved to within this 0.3mm tolerance, although $\pm 0.5\text{mm}$, equivalent to 0.19% of the test section diameter, is claimed for practical purposes. This tolerance contrasts with $\pm 1.5\text{mm}$, or $\pm 0.58\%$ of the pipe diameter when positioned manually.

Thus an improvement of $\times 3$ in absolute positioning was achieved by using the developed, encoder based instrument. Practically the utility of having an easy-to-operate, single handed, repeatable mechanism for setting the probe location greatly facilitated all the profiling experiments.

5.5.4 Development of improved data acquisition software; AutoCal

Measuring the performance of the battery full bore EFM in the laboratory at Cranfield, although technically successful, had proved to be time consuming. Acquisition of precision digital data from the transmitter RS232 port had been captured using Hyperterminal. This was a program for handling serial communications which was first part of the Microsoft Windows NT operating system and then migrated to Windows 95. Moving large amounts of data from the test files into Excel for analysis could not, for the planned probe calibration and field profiling, be practically supported because of the time involved in the separated tasks

To solve this problem a specification was developed, around which a program running on a standard PC was developed. It comprised the following elements:

- (a) Dual inputs from RS232 to allow recording of data from two meters; designed for either/or battery meter and/or mains meter.
- (b) Manual entry of desired run time/data numbers, operator information, run/contract details, etc, so as to provide the equivalent of the lab notebook but in accessible electronic form.
- (c) Automated start and stop with synchronous timing of data ports so that the two channels contained data for the same period.
- (d) Archiving of raw digital data to an Access database, along with all operator details, such that full archiving and traceability could be achieved
- (e) Visualisation, in real time, of the incoming data in order to understand and check test progress.
- (f) Sufficient inbuilt calculation to display key statistics at the end of each test directly to the operator, on screen.
- (g) The ability to recall past tests and show the summary screen.
- (h) The ability to have multiple runs included within one overall saved filename, i.e. to group individual data records under one event – a meter calibration.

The result of the above can be illustrated with reference first to the probe rotation experiment. This experiment required multiple tests; a high degree of precision; exact and repeatable data capture; and the ability to recall all the data for analysis.

Figure 5.18 shows an AutoCal screen shot of one run with the probe rotated by 7 degrees.

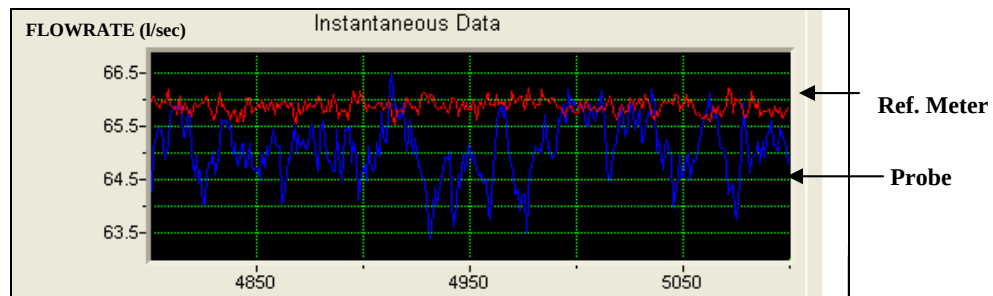


Figure 5.18: Detail of AutoCal data logging: probe rotated by 7degrees

The utility shown by the AutoCal program in visualising discrete flow features associated with the operation of the probe is clearly demonstrated, e.g. following rapid movement of the probe, one can observe that the probe output signal continues to oscillate, thus reflecting the hydraulics local to the probe tip despite the bulk flow

remaining relatively stable; blue indicates the probe signal and red that for the reference meter.

A second example to show how useful the program was when conducting experiments is shown in figure 5.19. This figure illustrates the AutoCal summary screen which appears after every run. There are three I/O areas related to instantaneous data, results and general information.

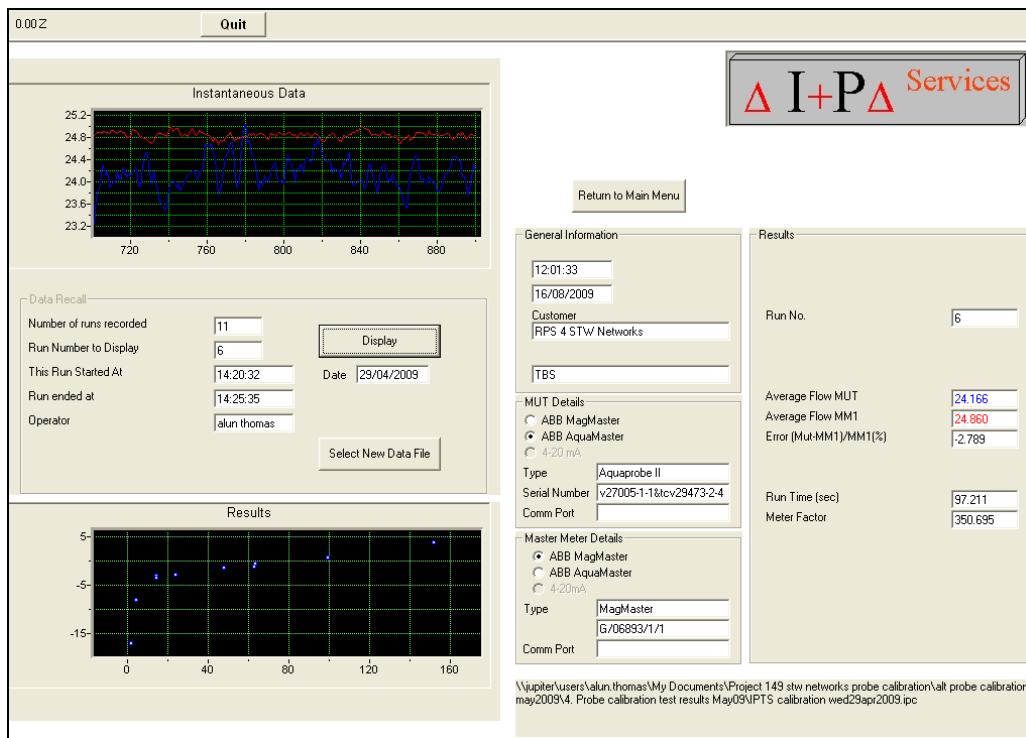


Figure 5.19: Example AutoCal screen shot; rotated probe at 15degrees

In addition the file path is displayed, along with the key statistics. These are: average MUT flow; average master meter flow; the run time; the meter factor - calculated from the MUT and master meter readings and the MUT error. In addition the date, time, the specific run, the total number of runs in the file and the name of the operator are all shown.

To aid the operator, feedback on progress is provided by plotting of the flow, point by point, as the test progresses. At the end of the test the full dataset is shown.

The developed software thus addressed the significant data acquisition difficulties which were identified during the original Cranfield laboratory work, i.e enabling time efficient collection of experimental data and creating traceable data archives amenable to subsequent analysis.

5.5.5 UKAS calibration history and performance of the IPTS master meter

In line with standard practice, calibration of the 200mm IPTS EFM master meter would have normally been undertaken using a pulse counting method referenced to the Hams Hall gravimetric tank. With the development of the AutoCal software a change to the

calibration method was required, replacing digital data in place of the pulse data. Making such a change made it possible to operate the IPTS as a master meter in digital output mode.

However, prior to starting probe calibration using the developed software and the master meter, evidence was gathered to demonstrate that changing to a digital calibration for the reference was technically advantageous. To do this a series of individual calibrations were undertaken over time, with each calibration measuring the flowrate over 13 points ranging from 5 l/sec to 150 l/sec[73]. For selected calibration runs data was collected using the pulse and the RS232 digital data streams in order to evaluate the relative uncertainties associated with each. Using the formal analysis method detailed in Appendix 9, values were then derived for mean and linear meter factors applicable to the pulse and digital data streams; together with their associated uncertainties. These uncertainties were similarly calculated in accordance with Appendix 9. Note, however, that in a departure from conventional analysis [74], the random uncertainty component for the statistics calculated here are scaled by the student t value rather than a factor of two. This reflects the reality that the population size for the meter calibration testing consists of a relatively small number of points.

Figure 5.20 shows the results of these calibrations between October 2003 and April 2009, illustrating the long term performance.

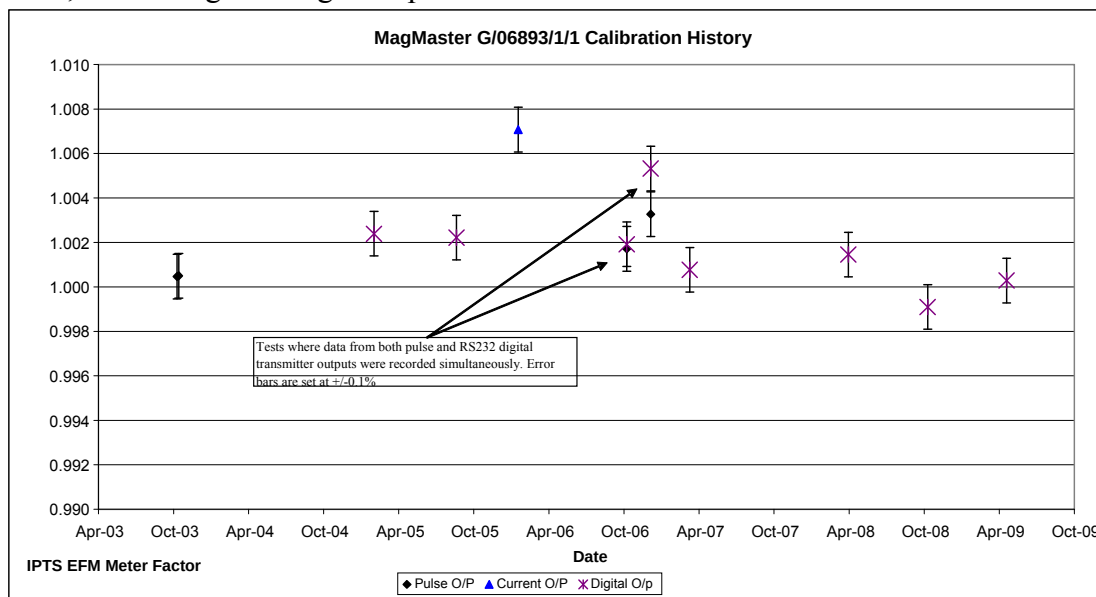


Figure 5.20: MagMaster G/06893/1/1 calibration history

Appendix 6, 7 and 8 provides details of the spreadsheet which utilised the AutoCal software and adhered to the number of data samples representing the optimum use of rig time and accuracy. This had been determined as 300 points for all except the lowest flows where 500 points were recorded. As the pulse and digital calibrations were undertaken during the same run, this meant that whilst the time for individual runs varied, the test periods over which pulses and digital data were logged was the same.

Using the statistical approach detailed in Appendix 9 two formats are available to describe a calibration from the recorded data. The first is that which delivers a mean fit meter factor. This is calculated as independent of the flow rate.

The second format arrives at a linear fit meter factor where the meter factor is related to the flow rate and is expressed in the form of $MF(\text{rate}) = A \text{ (a constant)} + B \cdot \text{flowrate}$.

In both cases the uncertainty of the laboratory must be included and contributes to the overall uncertainty associated with the instrument being tested. Practically, because the probe calibration methodology simultaneously logs the digital output of the probe and the IPTS master meter it was important to determine the master meter performance and to assess the range of uncertainty associated with the meter factor derivation; whether mean fit or linear fit.

Tables 5.3 and 5.4 show the results of the December 2006 master meter calibration and the values derived for meter factor and associated uncertainty.

Meter Factor (MF) Mean value fit	Uncertainty Components at minimum, mean and maximum calibration tests		
Nominal EFM flowrate	Min 5 l/s	Mean 74.5 l/s	Max 150 l/s
	Bias from slope		
Pulse	0.36%	0.00%	0.39%
Digital	0.01%	0.00%	0.01%
	Random Uncertainty component		
Pulse	0.24	0.14	0.25
Digital	0.06	0.04	0.07
	Total uncertainty (mean fit) – bias component plus random uncertainty component		
Pulse	0.62	0.17	0.66
Digital	0.13	0.11	0.13
Summary of Differences in Pulse and Digitally Derived Mean fit Meter Factors			
PULSE derived meter factor	1.003274	(See s/sheet fit)	+/- 0.66%
DIGITAL derived meter factor	1.005328	(see s/sheet fit)	+/- 0.13%
Difference between the pulse and digital derived mean meter fit factors = -0.204%			

Table 5.3: Derivation of mean fit IPTS EFM meter factor

Meter Factor (MF) Linear fit (A + B flowrate)	Minimum, mean and maximum calibration test flowrates		
Nominal EFM flowrate	Min 5 l/s	Mean 74.5 l/s	Max 150 l/s
MF from pulse calibration	1.0068943	1.0032738	0.9993426
MF from digital (RS232) cal'n	1.0052021	1.0053275	1.0054637
Factor 'A' Linear fit MF equation	Random Uncertainty component at given the specific flowrate		
Pulse calibration A = 1.007147	0.26	0.17	0.27
Digital calibration A = 1.007147	0.12	0.11	0.12
Difference between pulse and digital random uncertainty	0.14%	0.06%	0.15%
Ratio of pulse to digital random uncertainties values	4 to 1	3.5 to 1	3.6 to 1
Total uncertainty (linear fit) – 0.1% laboratory component – created by adding in the published UKAS.			
Pulse	0.26%	0.17%	0.27%
Digital	0.12%	0.11%	0.12%
Summary of Differences in Pulse and Digitally Derived linear fit meter factors; referenced to a flowrate of 65.51/sec			
Linear fit PULSE derived meter factor	1.003741	+/- 0.27%	
Linear fit DIGITAL derived meter factor	1.005311	+/- 0.12%	
Therefore, at the reference flowrate of 65.5 l/s, the difference between pulse and digital linear fit Meter Factor is = -0.156%			

Table 5.4: Derivation of linear fit IPTS EFM meter factor

From these tables the digital calibration method is shown to yield an improvement over that using pulse counting, with decreased values for the random uncertainty component in both mean fit and linear fit analyses.

Comparison between meter factor values derived using			different technique s
PULSE derived linear fit	1.003741	+/- 0.27%	A difference of - +0.047% ; relative to the mean fit
PULSE derived mean fit	1.003274	+/- 0.66%	
DIGITAL derived linear fit	1.00531 1	+/- 0.12%	A difference of - 0.002% relative to the mean fit
DIGITAL derived mean fit	1.005328	+/- 0.13%	

Table 5.5: Master MF comparisons: digital and pulse using linear fitted data

Selecting the linear fit approach table 5.5 summarises the differences between use of pulse counting and direct digital data logging.

With both approaches digital data acquisition improves performance from that using pulse counting, with a ratio between the calibration random errors of approximately $\times 4$ lower for the digital method. When the laboratory error component is included the total calibration uncertainties at the specific flows shown in the tables reduce by approximately $\times 2$.

Summary of the improvements in describing the master meter calibration

By combining digital, not pulse derived data with a specialist piece of software, AutoCal, the technical description of the master meter calibration can be improved by a factor of two, with the random uncertainty component reducing by between 3.5:1 and 4:1 across the flow range.

5.5.6 Results of I.P.T.S profile definition

Construction of the IPTS planned to use the assembly as a true portable transfer standard. This would have allowed checking of calibrations at manufacturers and eliminated the multiple sources of uncertainty which have caused inter-laboratory probe calibration to remain contentious. However, characterisation of the IPTS section velocity profile showed that technically it was not possible to attain the level of confidence in F_p necessary to be able to use the section as a reference against which the performance of battery EFM probes could rigorously be tested.

In the following section a description of the work undertaken to assess the velocity profile of the IPTS section is given, illustrating the difficulties which were encountered and which lead to rejection of the original combined master meter and probe test section concept.

Characterisation of the IPTS profile utilised the same beam pitot method as had been employed to measure that of the 260mm reference pipework. However, because of the lack of thickness of the IPTS stainless section, welding industry sized standard bosses onto the thin tube was advised against. The solution found was to drill and tap holes into the 212mm pipe and then weld tube section, not standard bosses, onto the pipe. See figure 5.16. Plastic inserts were then fitted into the tube section, through which the beam could be mounted.

The significant difficulty with this arrangement showed itself to be the inability to maintain a smooth surface on the inner face of the IPTS tubing in the vicinity of the tapping. See figure 5.15. At 212mm inner diameter, the IPTS cross section was 33% smaller than the reference pipework making the accurate positioning of the pitot much more demanding.

The results of the beam pitot profile are shown in figure 5.21 and are placed alongside the theoretical Pai curves. Note that the flows of 42l/s, 96l/s and 128l/s were chosen to be equivalent to the test velocities used when profiling the 260mm reference pipework section.

In contrast to the beam pitot results for the 260mm reference pipework, one can observe significant differences between Pai and the data measured. This therefore prompted a check on the likely size of the error contribution which different data integration

methods might contribute, and in particular the sensitivity of Fp as related to the number of points in the profile.

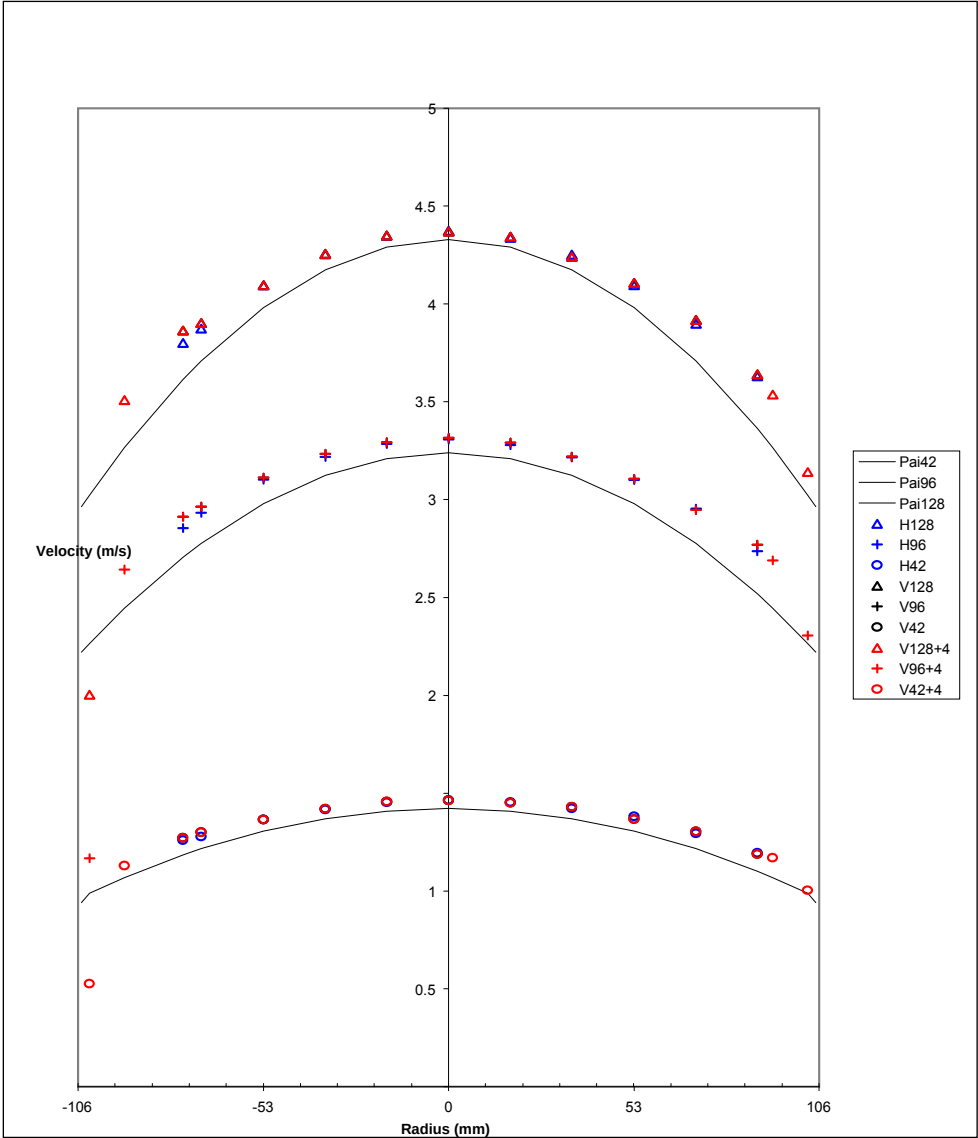


Figure 5.21: Insertion probe transfer standard - 212mm - profile attempts

Profile type =		Theoretical	H - Horizontal North-South	V - Vertical (Top-Bottom)
Line	Pai42	42 l/s		
Line	Pai96	96 l/s		
Line	Pai128	128 l/s		
Blue triangle	H128		128 l/s	
Blue cross	H96		96 l/s	
Blue circle	H42		42 l/s	
Black triangle	V128			128l/s
Black cross	V96			96l/s
Black circle	V42			42l/s
Red triangle	V128+4			128l/s; +4pnts
Red cross	V96+4			96l/s; +4pnts
Red circle	V42+4			42l/s; +4pnts

Table 5.6: Key to IPTS profile results graph

Table 5.7 shows the outcome of the comparison.

IPTS 212mm Flowrate (l/sec)	Pipe Reynolds number, Re	Von Karman - "m"	H runs (trapez- oidal)	H runs (11point cubics)	Difference ; trapez- cubics (%)
128	766,000	8.29	0.701	0.888	21.1
96	574,000	7.95	0.701	0.886	20.9
42	251,000	7.28	0.696	0.879	20.8
average			0.699	0.884	20.9

Table 5.7: Difference between trapezoidal and cubics integration

The significant difference between the simple trapezoidal and cubics integration methods strongly suggested that more profile points were required and accordingly more data was collected. These additional data are shown in figure 5.21 as V42+4, V96+4 and V128+4.

Table 5.8 lists the summary test data, showing the cubics integration values for Fp. Where a "+" is shown, integration of the addition four points i.e. a 15 point profile, is indicated.

Flow(l/s)	Vel(m/s)		Profile		%diff rel to "+" values		
128	3.63		H	0.861	1.29		-0.69
			V	0.867	2.00		H to V diff %
			V+	0.850			
				96			
96	2.72		H	0.860	2.50		-0.58
			V	0.865	3.10		H to V diff %
			V+	0.839			
				42			
42	1.19		H	0.846	1.56		-2.20
			V	0.865	3.84		H to V diff %
			V+	0.833			

Table 5.8: Summary of IPTS profile factors – all runs

The key observation of table 5.8 is that Fp is lowered, irrespective of the flow, when the extra four profile points are added. Indeed, as the velocity drops, the discrepancy between the 11point and 15point derived values of Fp for the vertical profile increases from 2.0% to 3.8%. Additionally the horizontal to vertical profile differences similarly increase from a value of -0.69% at 128l/s, equivalent to 3.6m/s, to -2.20%, equivalent to 1.2m/s.

In summary it was concluded that, although increasing the number of samples in the IPTS section profile, from eleven to fifteen, had improved the estimate of the IPTS Fp, the confidence with which the IPTS profile measurements could be repeated was unacceptable. In reaching this conclusion account was taken of the increased uncertainty associated with the extra data points resulting from the very small differential pressures generated by the pitot and the significant difficult in accurately positioning the probe.

5.5.7 Estimation of the reference section profile uncertainty

Following the decision to adopt the 260mm reference section as the preferred pipework location when calibrating probes, an assessment of the uncertainty associated with this location was undertaken. The following notes apply to the assessment:

1. The uncertainties for the differential pressure measurement and for the probe have been split into two components, systematic and random. The systematic component is assumed to cancel out for $V_{\text{mean}}/V_{\text{cl}}$. The random component is based on the average standard deviation found over all the test points.
2. To determine the uncertainty of the average, the number of independent points during a test period was assumed to be 10. Although this could be viewed as an arbitrary value, it regarded as a reasonable and representative figure which is used elsewhere for flow devices; averaged over 1 minute. [75]
3. The standard deviation, where calculated for measurements, is doubled to give expanded uncertainty and then halved because the square root of the differential pressure is used. (Flow, as derived from the beam pitot data is related to the square root of differential pressure).
4. Uncertainty for the integration method is assumed to be 0.5% [29].
5. Positional error has been shown from previous investigations to be small.
6. Flow stability is a factor in the calculation of the overall profile uncertainty, given that the tests points are recorded over time. The Hams Hall UKAS facility claims stability for flow of typically 0.5%. [75] which will be reduced by the averages taken.

The uncertainty on the **PITOT** profile factor ($V_{\text{mean}}/V_{\text{cl}}$) at Hams Hall can be derived examining and combining the individual uncertainty components as follows:

Uncertainty (U) on V_{mean} :

Systematic differential pressure (d.p.) : cancels with V_{cl}	=0.0%
Random differential pressure :	
the d.p. standard deviation was measured as 4.6% ;	
creating an uncertainty (U) for the 13 point traverse	
equal to ($4.6 \times 2/2/\sqrt{10}/\sqrt{13}$)	=0.4%
U from use of the method of cubics	=0.5%
U due to positional errors (from previous investigation)	=0.05%
U due to flow stability	
Laboratory statement of stability is 0.5%;	
creating an uncertainty(U) equal to ($0.5/\sqrt{10}/\sqrt{13}$)	=0.05%

Uncertainty on V_{cl} :

Systematic differential pressure (d.p.) : cancels with V_{mean}	=0.0%
Random differential pressure –:	
the d.p. standard deviation was measured as 3.8%;	
creating an uncertainty (U) equal to ($3.8 \times 2/2/\sqrt{10}$)	=1.2%
U positional errors (typical slope from CL is 0.05% per mm)	=0.05%
U due to flow stability-laboratory is 0.5%, so $U=(0.5/\sqrt{10})$	=0.16%

Combined uncertainty on the PITOT derived profile factor: =1.4%

The uncertainty on the **PROBE** profile factor ($V_{\text{mean}}/V_{\text{cl}}$) at Hams Hall can be derived examining and combining the individual uncertainty components as follows:

Uncertainty (U) on V_{mean} :

Probe systematic U due to the calibration factor: cancels with V_{cl}	=0.0%
Probe random U :	
the standard deviation of the point flow was measured as 2.0% ;	
creating an uncertainty (U) for the 11 point traverse	
equal to $(2.0 \times 2 / \sqrt{10} / \sqrt{11})$	=0.4%
U from use of the method of cubics	=0.5%
U due to positional errors (from previous investigation)	=0.05%
U due to flow stability	
Laboratory statement of stability is 0.5%;	
creating an uncertainty(U) equal to $(0.5 / \sqrt{10} / \sqrt{11})$	=0.05%

Uncertainty on V_{cl} :

Probe systematic U due to the calibration factor: cancels with V_{cl}	=0.0%
Probe random	
the standard deviation of the point flow was measured as 1.4% ;	
creating an uncertainty (U) equal to $(1.4 \times 2 / \sqrt{10})$	=0.9%
U positional errors (typical slope from CL is 0.05% per mm)	=0.05%
U due to flow stability-laboratory is 0.5%, so $U = (0.5 / \sqrt{10})$	=0.16%

Combined uncertainty on PROBE derived profile factor: =1.1%

In regard to the calculation of site, not laboratory, uncertainties on V_{mean} , the probe uncertainty would be included and the uncertainty on V_{cl} removed. This would suggest that the probe uncertainty would then become the predominant component.

5.6 EFFECT OF PROBE ROTATIONAL MISALIGNMENT

5.6.1 State of knowledge

One of the classically discussed sources of probe error is due to axial longitudinal misalignment i.e. yaw. Herne-Smith[76] provides figures for an insertion turbine which reference Miller [70] who states an approximate 4% error at 10° yaw. In the context of the work here two points are relevant. First, a misalignment of 10° is visually obvious to even the untrained eye and is most unlikely to occur accidentally. This is because the human eye is very sensitive to angular discrepancies and even when a little of the pipe can be seen, an error of more than 1° or 2° would be unlikely to go unmissed. Secondly, a turbine has quite different hydraulic characteristics to a smooth cylinder and there would be little reason to validly extrapolate from the mechanical meter data. Importantly, the manufacturer of the battery EFM probe had not published data related to angular misalignment, thereby prompting the need to investigate this aspect of performance.

5.6.2 Test Method Adapted When Investigating Probe Misalignment Errors

Angle Setting: The error in setting small angles accurately can be challenging if attempted visually and requires recourse to basic geometry to ensure precision. With a probe mounted on the centre line, use of optical surveying equipments was impractical and so the idea of using a probe top-box mounted, low powered laser level was invented.



Figure 5.22: Top-box mounted laser (glued)



Figure 5.23: Probe rotation tests

Figure 5.22 shows the set-up adopted in the laboratory with the laser level effectively glued to the top of the probe housing, which itself is jig welded to the probe stem. This arrangement thus ensured that the probe electrodes were precisely maintained orthogonal to the direction of flow.

By measuring the distance to the far wall of the laboratory and then across to the laser light falling on the far wall away from the pipe centre line, the required probe rotation could be accurately set and reliably repeated. The arrangement can be seen in figure 5.23 with the red laser light visible on the far wall of the laboratory.

A total of 21 tests were run. These included repeats at four points, 0, 5, 6 and 7 degrees, plus reproducibility tests at 0, 2, 7, 10 and 15 degrees, so forming a comprehensive evaluation. The results are shown in table 5.9.

Test Point or Run Number	Angle of rotation (degrees)	Probe Error (relative to Digital Master Meter) (%)	Normalised Standard Error (NSE)	Standard Deviation	Max Velocity (m/sec)	Minimum Velocity (m/sec)	Average Velocity (m/sec)	Probe Velocity NSE	0.075	Test Point or Run Number	Reproducibility (% change)
1	0	0.075	0.72%	9.01E-03	1.264	1.215	1.244	0.72%	0 degrees	2	
2	0	0.178	0.76%	9.47E-03	1.269	1.218	1.244	0.76%		21	0.03%
3	7	-2.787	0.91%	1.10E-02	1.239	1.175	1.206	0.91%			
4	7	-2.675	1.80%	2.20E-02	1.271	1.139	1.226	1.80%	7 degrees	4	
5	6	-0.94	0.74%	9.16E-03	1.253	1.203	1.231	0.74%		17	0.01%
6	6	-0.7	0.81%	9.96E-03	1.257	1.205	1.234	0.81%			
7	5	-0.506	0.89%	1.09E-02	1.257	1.194	1.233	0.89%	2 degrees	10	
8	5	-0.824	1.07%	1.31E-02	1.253	1.180	1.229	1.07%		20	0.27%
9	4	-0.727	0.75%	9.23E-03	1.258	1.202	1.231	0.75%			
10	2	-0.027	0.77%	9.59E-03	1.270	1.217	1.241	0.77%	10 degrees	13	
11	-7	-0.377	0.80%	9.93E-03	1.259	1.204	1.237	0.80%		18	0.18%
12	-7	-0.594	0.97%	1.20E-02	1.262	1.204	1.234	0.97%			
13	10	-2.283	0.84%	1.02E-02	1.243	1.187	1.213	0.84%	15 degrees	14	
14	15.1	-4.934	0.78%	9.15E-03	1.203	1.149	1.177	0.78%		19	0.28%
15	-5	-0.012	0.90%	1.12E-02	1.271	1.208	1.241	0.90%			
16	-2	0.134	0.78%	9.73E-03	1.266	1.214	1.242	0.78%			
17	7	-1.222	0.87%	1.06E-02	1.253	1.194	1.226	0.87%			
18	10	-2.384	0.82%	9.97E-03	1.240	1.187	1.211	0.82%			
19	15.1	-5.046	0.96%	1.13E-02	1.215	1.139	1.180	0.96%			
20	2	-0.399	0.87%	1.07E-02	1.266	1.205	1.238	0.87%			
21	0	0.193	0.80%	1.00E-02	1.269	1.215	1.243	0.80%			

Reproducibility Definition: $((\text{Abs}(\text{Repeat Run Average Velocity} - \text{First Run Average Velocity}))/\text{Abs}(\text{First Run Average Velocity}))$

Table 5.9: Test Sequence; Probe rotation and Percentage Error

All data collected was digital and utilised the newly developed AutoCal program, built on the RS232 outputs from the full bore master meter and probe under test. A minimum of 100 values were recorded at each rotation setting and the flowrate in the pipe held steady, as per a standard calibration run.

5.6.3 Results of Probe Misalignment

Figure 5.24 plots the probe error curve for the data in Table 5.8 above. Imposed on the data are two trendlines. The upper trendline represents the measured probe output error. The lower the resolved component of the centre line velocity i.e. centre line velocity*cos(angle of rotation).

Observations from Table 5.9 and from the error plot in figure 5.24 are that:

- Repeatability and reproducibility for the probe output over the complete range of angular misalignment was very good. This is a reflection both of the method of recording, the utility of the automated software, the number of samples and the stability of the flow over the duration of the test.
- Sub 4° the errors lie within a very small band with maximum of +0.19% and minimum -0.40%. This error is an order of magnitude smaller than the error value for turbine yaw quoted by Miller [70].
- The effect of angling the probe across the flow, which should broadly follow the theoretical lower trendline, was smaller than expected. This is evidenced by the actual errors and the upper trendline. The battery EFM probe is therefore less sensitive to directional alignment than would be predicted.

- The manner in which the probe is rotated can significantly affect the error and is as important as the absolute size of the mis-alignment. The evidence for this is illustrated by the third and fourth test points which were taken at 7 degrees, following the initial centre line runs, contrasted with the later run at 7 degrees which was part of a smooth sequence.
- Moving initially from the centre line involved sharply rotating the probe and resulted in error values which were not in line with the general trend created when the probe was moved incrementally: -2.73% error v -1.22% error. However, the repeatability of the probe output following the initial 0 to 7 degree shift was excellent, indicating that the hydraulic conditions close to the electrodes of the probe were stable.

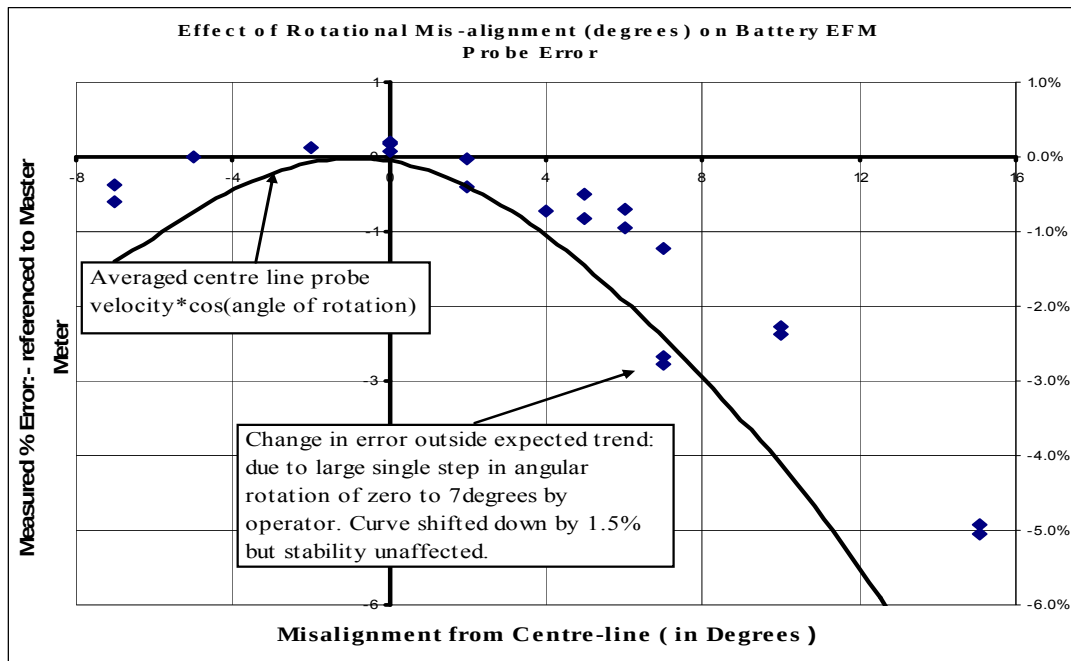


Figure 5.24: Effect of Rotational Mis-alignment (degrees) on Battery EFM Probe Error

- Examined for general symmetry the overall results show a skew away from the centre. This could be explained in a simple manner were there to be a difference between the geometric and actual probe centre lines. However, measurements indicate that this was not the case. An alternative explanation is that the coil assembly within the probe tip has been manufactured asymmetrically, leading to a distortion in the measured velocity.
- Figure 5.25 emphasises that the spread of probe minimum and maximum errors are very small across the range of flows. These errors are relative to the master meter and are derived from the measured velocities given in table 5.9.

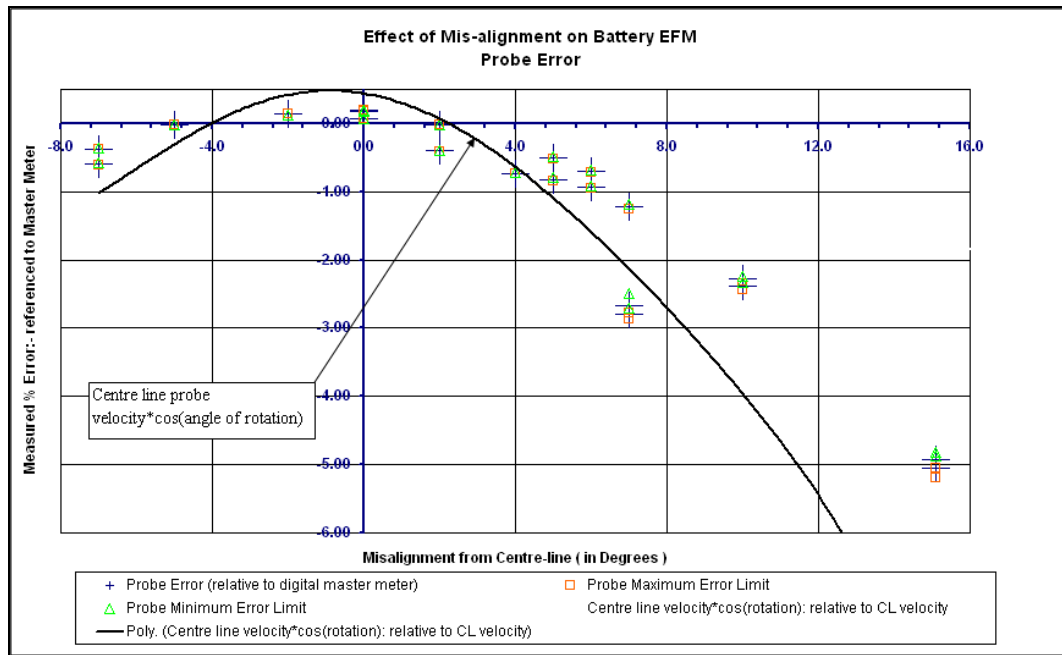


Figure 5.25: Effect of Rotational Mis-alignment (degrees) on Battery EFM Probe Error

Figure 5.26 shows that the Normalised Standard Error (NSE) for each of the data runs plotted against the rotation angle. Referring to the sharp rotation from 0 degrees to +7 degrees, point number 4 in table 5.9, it can be observed that the value of NSE for this run is the significantly larger than all others. One can conjecture that this reflects local hydraulic disturbance in the vicinity of the probe electrodes, leading to a higher noise component within the bulk flow signal. In addition, because of the stable nature of the readings, it has the appearance of a bi-stable characteristic.

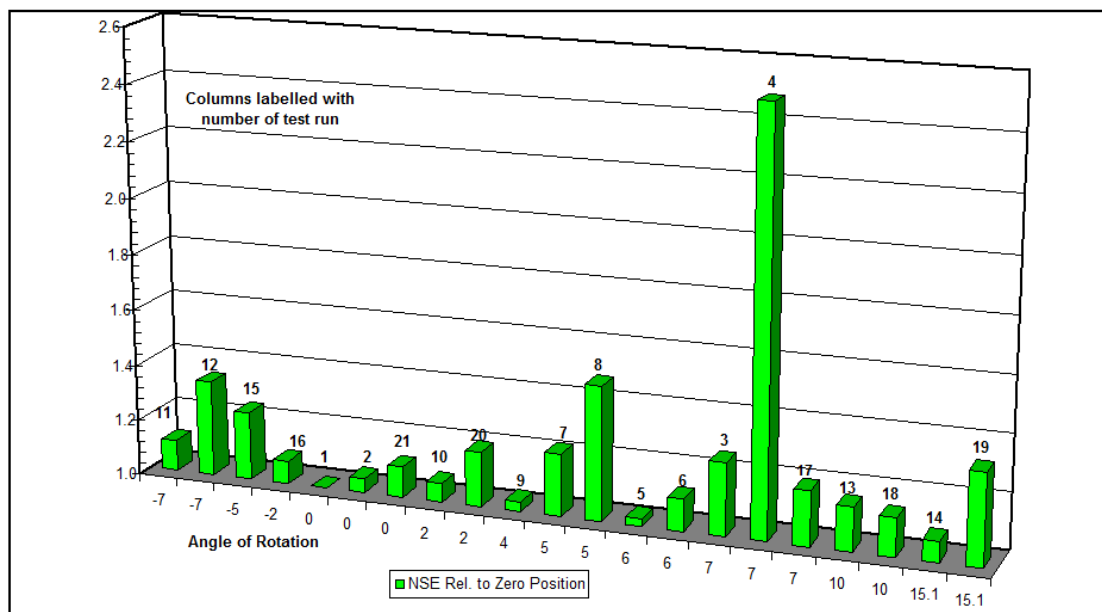


Figure 5.26: NSE Rel. to Zero Rotation Position (plotted by angle)

Nevertheless, the conjectured disturbance is stable in the short term, as evidenced by the repeatability data seen in figure 5.24 and listed in table 5.9. A previous report [77] of anomalous probe readings following probe alignment in the field had been made, but without relevant objective evidence as shown in figures 5.24 and 5.26, these reports had been attributed to poor practice on behalf of the operator.

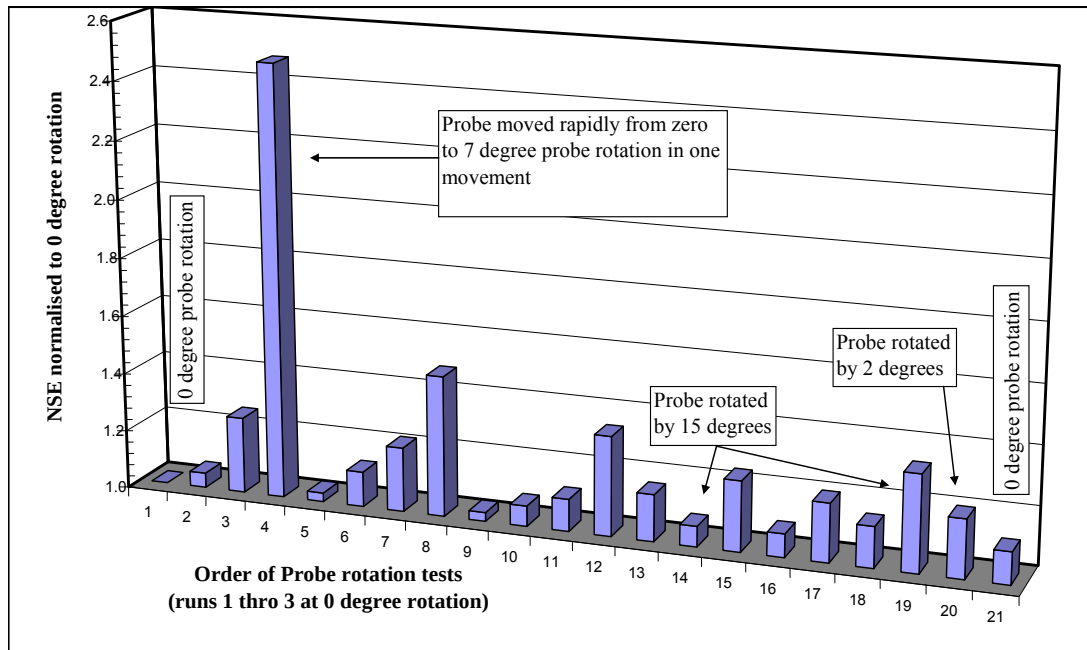


Figure 5.27: NSE normalised to probe zero rotation position (plotted in order of testing)

When the above NSE data is re-plotted relative to the centre line value, figure 5.27, one can observe that the normalised values of NSE for all test runs lie below 1.5, with an average of 1.16. However, for the run which followed the sharp rotation of the probe, the relative NSE is 2.48, more than twice the average.

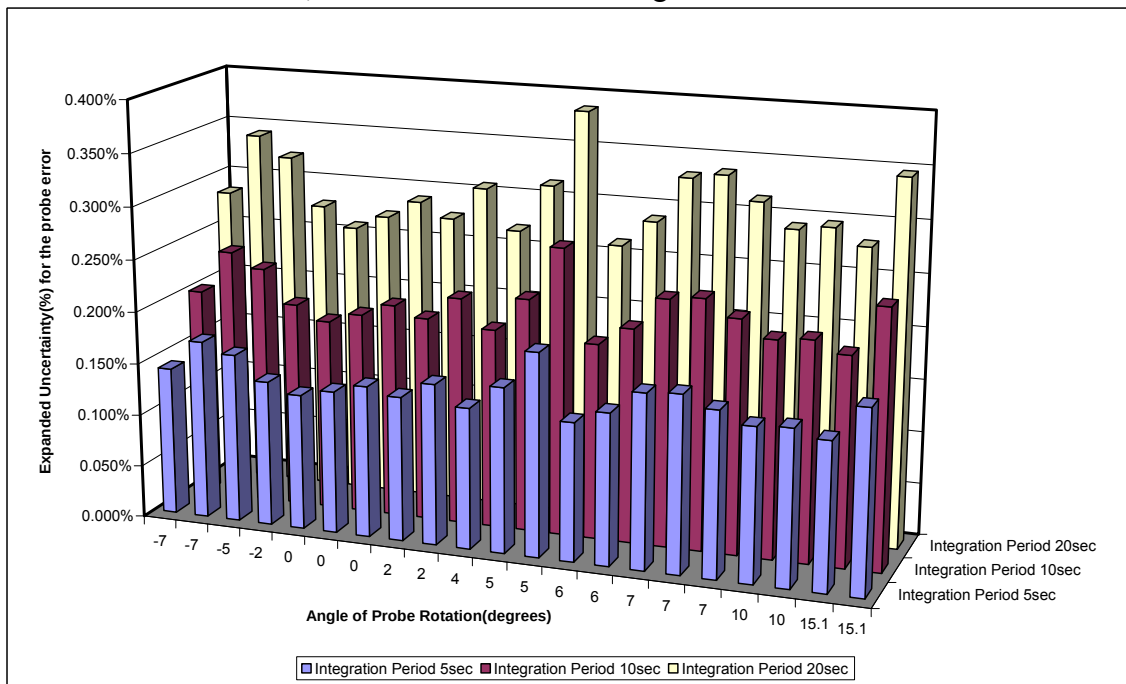


Figure 5.28: Probe error expanded uncertainty for different integration values

Finally, figure 5.28 illustrates the range in the estimated uncertainty associated with the probe error against the angle of rotation. The expanded uncertainty is plotted with different sample sizes defining the integration period and is intended to demonstrate the importance of understanding the analysis variables. Both the variation and size of the computed probe error uncertainties are shown, with the spread in values varying widely depending upon the conditions set for the analysis.

When combined and placed in the wider context of the experimental run reproducibility of between 0.01% and $\pm 0.28\%$ of reading, (see table 5.9), the range of expanded uncertainties taken from figure 5.28 of between 0.13% and 0.39% add together such that the influence of practical misalignment can be expected to fall within better than 0.5%.

In arriving at this 0.5% overall result it is clear that the size of the data sample and the detail of the statistical analysis are strong influences.

5.6.4 Summary finding re probe rotation error

The laboratory results have carefully defined the performance of the battery insertion EFM probe. The conclusion is that, unlike the insertion mechanical turbine based designs cited by Miller [70], the influence of misalignment is far smaller. For practical situations where misalignment of 1 or 2 degrees is representative, the error has been shown to be an order of magnitude smaller, lying in a band below half of a one percent.

An important limitation to the use of the probe has also been highlighted when deploying this type of design, with evidence from the laboratory tests indicating that it is important to avoid sharp rotation when aligning the probe.

5.7 PROBE CALIBRATION AND RE-CALIBRATION

5.7.1 Scoping of Calibration Test Range

Following the beam pitot measurements a series of trials were undertaken calibrating battery insertion EFM probes. The scope of the testing was to develop a test schedule which would be sufficiently wide to encompass characterisation of the probe, whilst remaining efficient in terms of rig time and utilisation. The tests were to be referenced to the manufacturer's calibration such that the Hams Hall schedule could provide a robust and traceable check. A range of test flows was therefore devised and is shown in table 5.10. The table additionally shows the manufacturer's Reynolds number values.

Hams Hall test rig	Flowrate l/sec	Mean velocity m/sec	Re value at 21degC	Re value at 24degC	Max to min Re ratio
260mm nom diameter	5	0.09	25,100	26,893	
(I+P standard flowrates)	18	0.34	90,200	96,800	
	100	1.88	501,000	537,867	
	150	2.83	751,900	806,800	32 to 1
	65.5	1.23	328,155		
ABB factory test rig					
(typical flowrates)					
207mm	5.36	0.16	33,800	36,200	
	33.85	1.01	213,200	228,800	
	66.45	1.97	418,600	449,200	13.3 to 1
ABB factory test rig					
207mm					
Certificate 06/95791	5.3384	0.16	33,500	33,900	
10-Nov-06	66.488	1.91	417,000	417,300	12.3 to 1
ABB factory test rig					
108.4mm			20.9degC		
Certificate 06/97616	10.047	1.09	120,400		1.6 to 1
17-Dec-06	16.029	1.74	191,700		

Table 5.10: Hams Hall and ABB test flows with Reynolds number (Re) test ranges

Survey data from a major water plc [72] had indicated that many meters operated within a Reynolds number range of 75 000 to 700 000. In contrast, the two sample calibration certificates from ABB, shown in figures 5.29 and 5.30, covered 33 500 to 417 000 and 120 000 to 192 000.

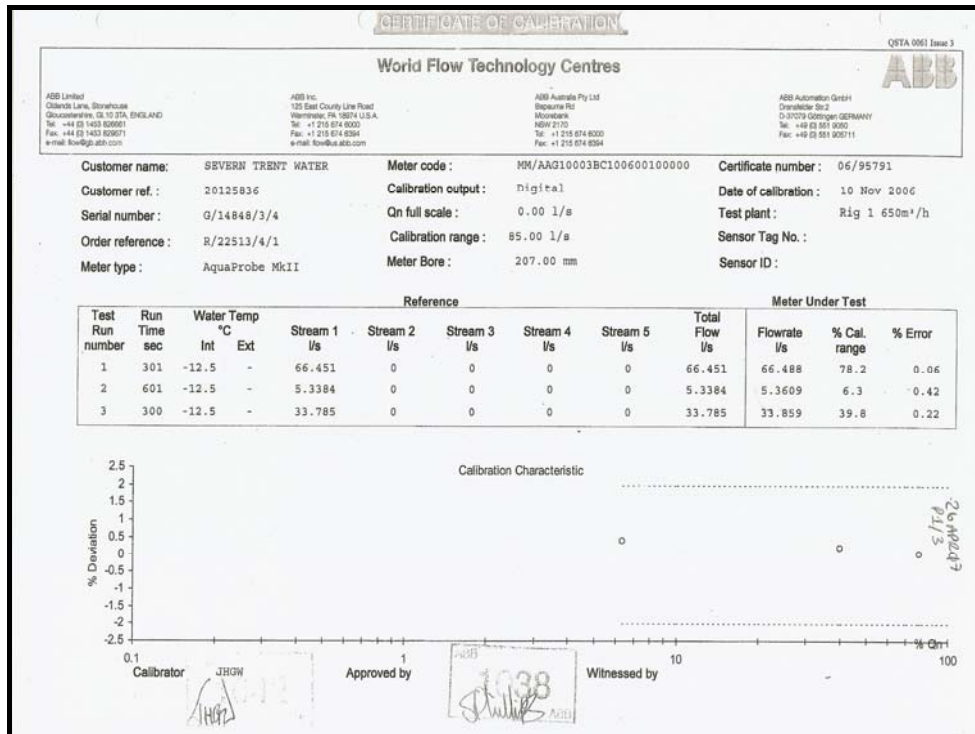


Figure 5.29: ABB calibration certificate; 10 Nov 2006

The latter range was deemed too restricted to be representative, whilst the former failed to include flow velocities of 0.1 m/sec or lower, which regularly occur in parts of the network. Note that the manufacturer calibrates with the probe on the centre line.

A final test schedule for the Hams Hall laboratory, suitably representative of the performance demanded of a battery EFM probe, was generated and ran from Re=12,500 or 2.5 l/sec in the reference pipework section to Re=1,000,000 equivalent to 200 l/sec measured in the 260mm reference section.

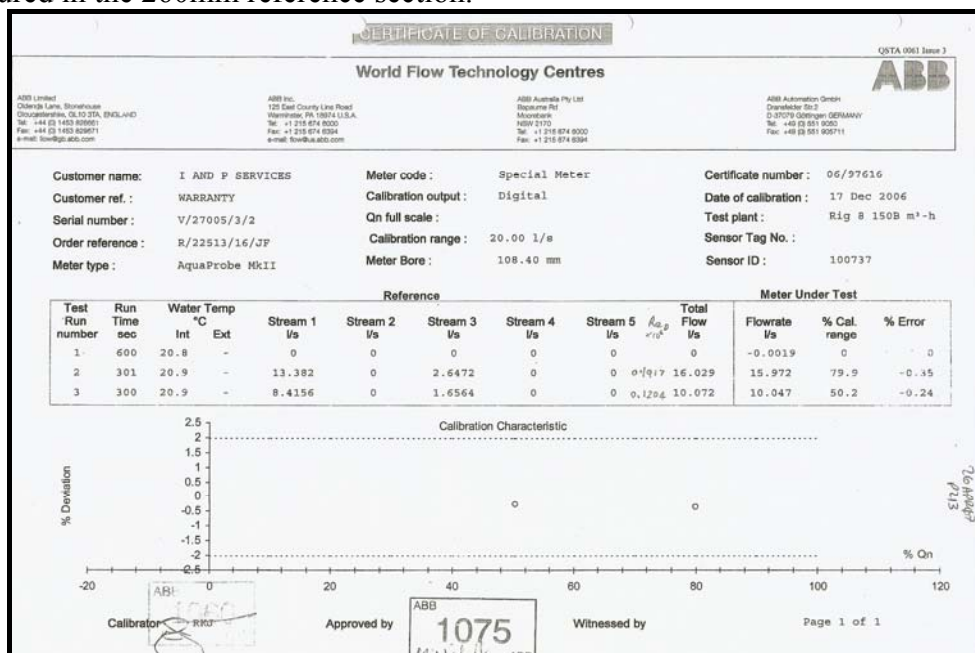


Figure 5.30: ABB calibration certificate; 17 Dec 2006

However, these test times were found to be too onerous/expensive and a compromise, reflecting the practicalities of probe calibration was made, setting the lower flow at $Re=25\,000$, 5 l/sec, and the upper $Re=500\,000$, 100 l/sec. Table 5.12 below lists this sequence and exceeded the manufacturer's wide-range calibration, including a test point at $Re=328\,000$, 65.5 l/sec.

Test No.	1	2	3	4	5	6	7	8	9
Flowrate	100	100	65	25	15	15	5	5	65

Table 5.11: Battery EFM Probe Calibration Test Sequence

This specific flowrate was included after reviewing a survey of operational sites[72] which indicated that a median WISPY meter would have an average velocity in the order of 1.23 m/sec under daytime conditions, during which WISPY meter verification, using a probe, was most likely to take place. Table 5.12 illustrates the relationship between pipe size, median site flowrates, velocity and Reynolds number taken from that survey.

Pipe Size(mm)	Flowrate l/s	Velocity	Reynolds number
1200	1500	1.33	1472000
250	100	2.04	471000
250	10	0.2	47000
150	36	2.04	283000
150	2	0.11	16000

Table 5.12: Typical Flow, Velocity and Re values for WISPY meter applications

At 20:1 turndown, the revised schedule was deemed to be able to provide a reasonable test of the probes published capabilities.

5.7.2 Derivation of a probe performance statement: interpretation of calibration data and uncertainty

A necessary requirement once the probe calibration test schedule had been formalised was the need to establish a formal statement for probe performance. Figure 5.31 shows a typical battery EFM probe calibration and illustrates the general shape of the calibration featuring a rising meter factor. The probe illustrated is that of probe C, the calibration details of which are listed in table 5.15.

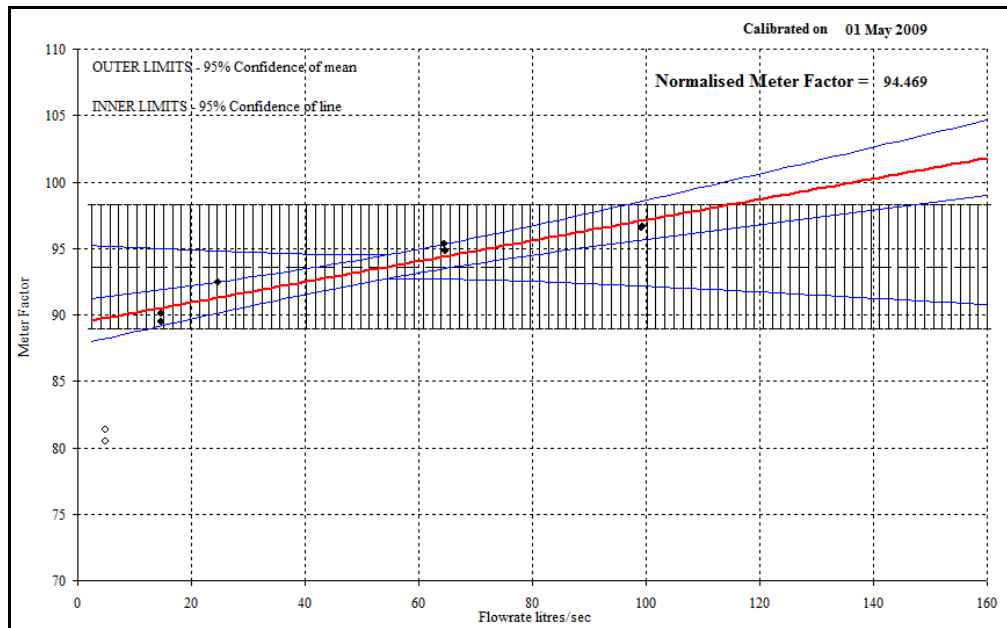


Figure 5.31: Flowmeter Uncertainty for Probe C

The detail and presentation of the probe calibration performance was, in contrast to that of the manufacturer, designed to illustrate the meter factor as calculated according to either (1) a linear-fit meter factor (MF) format given by $MF = (A + B \times \text{Flowrate})$ or (2) a mean-fit meter factor format which averages MF over the range of flows tested.

To aid understanding of the calibration tolerance, limit bars are added at the $\pm 5\%$ level and the 95% confidence limits for both linear and mean MF values added. In Figure 5.31 the linear-fit MF is shown as the red line; the horizontal mean-fit MF as the dotted black line; the 95% confidence limit for the mean-fit MF as the outer blue lines and the 95% confidence limit for the linear-fit MF as the outer blue lines.

The assessment of the uncertainty of the battery EFM probe characteristic is made over a specified range, which is typically 2.5 to 160 l/sec. This range reflects the original extended calibration test schedule and allows sight of the assessed performance for extrapolated flowrates.

For calculation of the linear-fit MF a format of $MF = (A + B \times \text{Flowrate}) \pm \% \text{ uncertainty}$ is adopted, where A and B are linear regression constants calculated for the data set selected. The alternative mean-fit MF is expressed only as $MF = (A \text{ Constant}) \pm \% \text{ uncertainty}$. For both MF formats the overall assessment is the combination of the random uncertainty of the data points plus a contribution from the Hams Hall laboratory, presently stated as $\pm 0.1\%$.

Appendices 5A(i), 5A(ii) and 5A(iii) give further details of the MF calculation method with an example of the procedure, data input, graphical output and uncertainty assessment sheets.

Examining figure 5.31, which is typical of the battery EFM probe design, the adoption of the mean-fit MF format has clear limitations. In particular, the slope of the probe

characteristic may vary considerably, which in turn will adversely affect the mean-fit MF figure. Thus, in order to standardise across different probes, a generic approach was adopted which normalised the MF to 65.5 l/sec or 1.23m/s, the median velocity for WISPY meters within Severn Trent Water.

For probe C, shown in figure 5.31, the complete uncertainty assessment, taken directly from the calibration certificate, is reproduced below and should be read in conjunction with the example given in Appendices 5A(i), 5A(ii) and 5A(iii).

Adopting the linear-fit MF format the calibration assessment yields the following statistics:

	Minimum	Mean	Maximum
Flowrate (litres/sec)	2.50	54.56	160.00
Linear-fit Meter Factor	89.577	93.620	101.808
Random Uncertainty (U)	1.71%	0.94%	3.04%
Total U (including lab)	1.72%	0.95%	3.05%

Table 5.13: Probe C calibration linear-fit meter factor assessment

However, the MF shown in table 5.13 is that which relates to the mean flow during the calibration. When normalised to 65.5 l/sec using the relationship $MF = (A + B \times \text{Flowrate}) \pm U\%$ and inputting the test specific regression constants $A = 8.9383E+01$ and $B = 7.7655E-02$, the revised “best fit” MF becomes equal to 94.469. This is the normalised value which is used to describe the probe MF calibration. Added to this is the associated uncertainty of the linear-fit MF characteristic for probe C, which from table 5.13 is no better than 3.05%. The summary performance statement for the linear-fit for probe C is therefore $MF=94.469 \pm 3.05\%$.

Alternatively one can use the mean-fit MF to arrive at the probe calibration characteristic. The details, again taken directly from the calibration certificate, are given in table 5.14.

	Minimum	Mean	Maximum
Flowrate (litres/sec)	2.50	54.56	160.00
Mean-fit Meter Factor	93.620	93.620	93.620
Bias from slope	4.32%	0.00%	8.75%
Total U (including lab)	6.03%	0.95%	11.79%

Table 5.14: Probe C calibration mean-fit meter factor assessment

The summary performance statement using a mean-fit for probe C is therefore $MF=93.620 \pm 11.79\%$. Thus, when utilising a mean-fit description of MF the value appears -0.90% lower than the equivalent linear-fit normalised figure. However, the associated performance uncertainty is almost four times larger.

In relation to the application of battery EFM probes for regulatory verification purposes, this difference is highly significant.

5.7.3 Effect of probe tip condition on performance calibration

The published literature makes no reference to performance effects related to probe tip condition. However, the detailed nature of the probe calibration curves recorded using

the Hams Hall reference section clearly show that probe tip condition is critical to maintenance of repeatability and reproducibility. Evidence of this sensitivity was seen in the recalibration of probe 12, the “control” probe kept in the laboratory and regularly recalibrated as a means to check the overall system integrity.

Figure 5.32 shows the output from Probe 12, V/142731/7/1 and transmitter V/142731/8/1, first at initial calibration and then after one year. Retained as a “control” it’s characteristic and MF were tightly documented. As seen, re-calibration after one year in storage, during which time the tip had been kept wet but not cleaned, saw a shift of +2.12% relative to its known MF. In addition the uncertainty of the MF increased to 2.55% from earlier values which ranged between 1.5-1.7%.

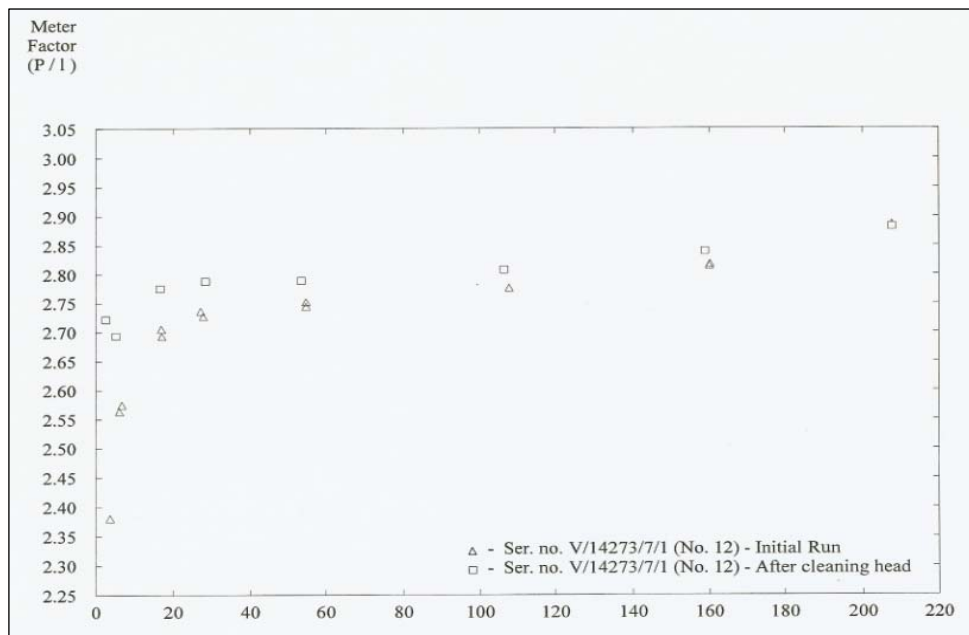


Figure 5.32: Output from Probe 12, at initial calibration and after storing for 1 year

As the control instrument the measured changes were relatively large and, unless a physical change could be demonstrated in the probe, the result would have cast doubt on the overall uncertainty of the process.

It was therefore decided to clean the probe tip surface and the electrodes using soap and water, gently applied with a nylon mesh pan cleaner to avoid any scratching of the surface. The result after this cleaning of the tip of probe 12 is plotted in figure 5.32 as the upper line.

Following cleaning the MF characteristic changed becoming realigned to within +0.5% of the value from one year earlier and in line with the predicted target value.

The value of U similarly reduced from 2.55% to a more representative figure of 1.65%, providing clear evidence that surface condition as well as physical, geometric probe tip condition is important.

Additional evidence concerning the sensitivity of the probe tip condition to overall battery EFM probe performance is seen in figure 5.33.

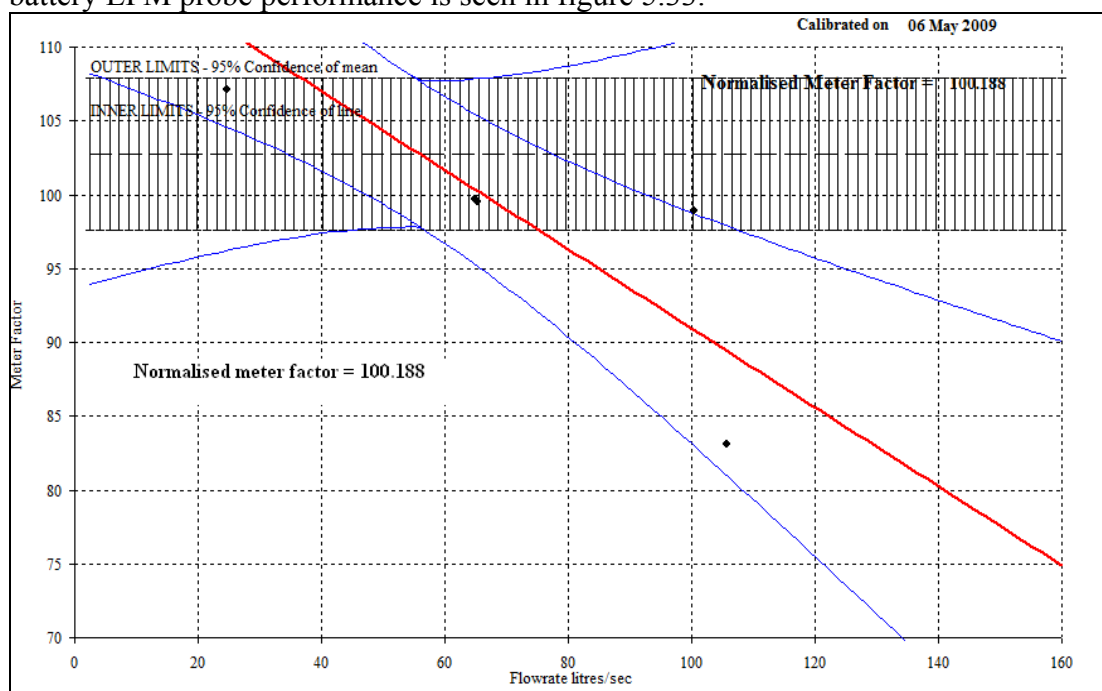


Figure 5.33: Flowmeter characteristic associated with damaged and scratched tip; Probe J

As seen, the slope of the calibration curve for probe J is negative, unlike the standard characteristic. This change in slope, allied to an increased uncertainty in the MF, is conjectured to be linked to the physical condition of the probe tip rather than its surface condition, the effects of which are seen for probe 12 in figure 5.32.

In the case of probe J clear visual evidence existed of the mechanical erosion of the probe tip lower radius, together with vertical scratching of the tip below and above the electrode location. Figure 5.33 reflects this condition with the MF significantly changed by 12.3% compared to a year earlier, when the probe tip condition was formerly examined and recorded as being in good condition. In addition to the change in the meter factor the associated uncertainty increased by 8.8% to a 14.8%. Such a value is unacceptable for an instrument deployed as part of a regulatory meter verification programme.

Photos representative of probe tip condition are given in Appendix 10 and illustrate the significant differences which occur over time during the working life of an insertion instrument.

On the basis of the evidence obtained from battery EFM probe re-calibrations using the traceable reference section and IPTS EFM master meter, failure to maintain an insertion battery EFM probe in respect of either

- (1) the cleanliness of the surface or
 - (2) the physical integrity of the probe tip geometry and radial curvature,
- will lead to significant or gross errors in meter factor, accompanied by greatly increased values in the meter factor uncertainty.

5.7.4 Probe performance and calibration: review of a sample of 1-year recalibration results

Following standardisation of an adequate and sufficient flow calibration test schedule, the performance of a batch of Severn Trent Water's probes was implemented with monitoring on a yearly basis.

Appendix 10 lists the detailed procedure and Appendices 6, 7, 8 and 9 the methods used to derive the meter factor and the associated uncertainties discussed in the following sections.

To demonstrate representative examples for these annual probe recalibration outcomes a sample of results is presented :

- (a) to illustrate the range of performances which are achieved by the battery EFM probe design following deployment as a profiling/verification tool, and;
- (b) to inform the underlying performance question, "How stable are insertion EFM meters over time".



Figure 5.34: Recalibration of 2m battery insertion probe

The sample results illustrate both the characteristic battery probe performance, the quality of the probe data and indicate the limitations of applying generic criteria to the technology, without recourse to the individual instruments.

Of importance to the water industry is the use of the battery probe within the regulatory process. The review of re-calibration results highlights how individual probes can vary.

Unless recognition is made of these variations the present meter verification process, which forms part of establishing the overall regulatory water balance data, cannot be adequately assessed in regards to its technical provenance.

Details of the recalibration performance of ten probes are detailed in Table 5.15.

Probe Pair	Date	Normalised Meter Factor A + B*Flowrate, +/-U%					Mean Meter Factor			
		A	B	Meter Factor (MF)	MF Cal Uncertainty	% Diff Normalised MF 2008/09	Meter Factor (MF)	MF Cal Uncertainty	% Diff Mean MF - 2008/09	Probe Class
A	2008	95.99	0.01	96.81	1.14	-1.5%	96.68	2.50	-1.0%	Good
	2009	94.54	0.02	95.93	1.14		95.72	3.44		+ve
					0.00			0.94		
B	2008	91.24	0.06	94.91	2.77	-1.7%	94.34	9.03	-0.3%	Good
	2009	89.72	0.08	94.89	3.44		94.06	12.25		+ve
					0.67			3.22		
C	2008	90.19	0.07	94.56	2.00	-0.9%	93.85	9.49	-0.2%	Good
	2009	89.38	0.08	94.47	3.05		93.62	11.79		+ve
					1.05			2.30		
D	2008	96.66	0.00	96.59	1.49	-1.9%	96.60	1.60	-1.4%	Good
	2009	94.80	0.01	95.30	1.68		95.21	2.51		Flat
					0.19			0.91		
E	2008	91.96	0.02	93.31	0.84	4.3%	93.10	3.16	5.4%	Shifted
	2009	95.93	0.05	99.20	0.87		98.08	6.82		+ve
					0.03			3.66		
F	2008	120.62	-0.25	104.25	13.08	-0.3%	106.92	37.66	-0.1%	Stable
	2009	120.22	-0.24	104.19	13.30		106.78	37.39		-ve
					0.22			-0.27		
G	2008	87.02	0.08	92.49	2.70	-6.3%	91.60	12.30	-10.8%	Bad
	2009	81.51	0.15	91.32	12.86		81.74	30.38		+ve
					10.16			18.08		
H	2008	86.64	0.09	92.59	2.39	-1.6%	91.62	12.80	-1.3%	Good
	2009	85.30	0.09	91.44	4.45		90.43	15.36		+ve
					2.06			2.56		
I	2008	90.67	0.07	94.93	3.10	-13.1%	94.24	10.35	-5.6%	Poor
	2009	78.77	0.19	90.92	10.59		88.94	32.52		+ve
					7.49			22.17		
J	2008	104.85	-0.09	98.84	5.97	12.3%	99.81	15.63	3.0%	Bad
	2009	117.72	-0.27	100.19	14.77		102.76	41.89		-ve
					8.80			26.26		
Note: Probe F has poor Characteristic										
Note: Values in Italics are the change in Cal uncertainty year to year										

Table 5.15: Results of the recalibration of ex field service insertion probes

Of the ten probes, half were classified as showing “good”, reproducible calibrations; four calibrations ranged from ‘bad’ to ‘poor’ and were deemed unsatisfactory; and one calibration showed a characteristic which was shifted in scale. For this latter probe it was concluded that operator interference or possibly internal transmitter hardware failure were to blame, rather deriving from influences arising from use or damage.

Detail of Probe B Performance.

The calibration characteristic of probe B is shown in figure 5.35. This is a typical example of a “good” battery EFM probe.

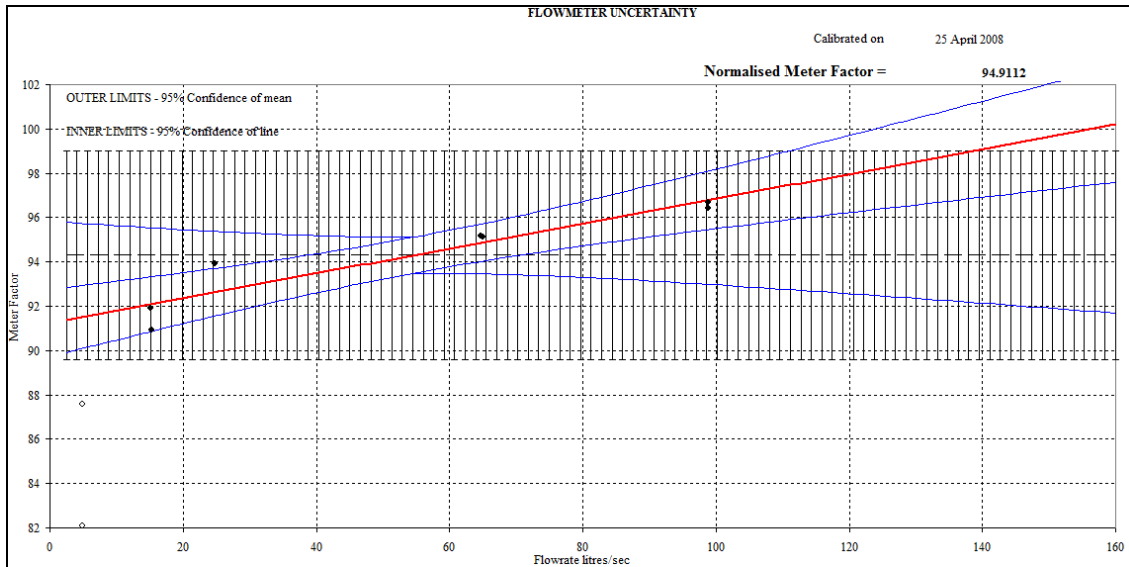


Figure 5.35: Flowmeter calibration for Probe B, 2008

The bars group a $\pm 5\%$ limit about the mean value for the probe meter factor, which is shown as a horizontal dotted line. The alternative statistical interpretation of the calibration data, represented by a linear meter factor which is related to flowrate and not constant over the flowrange, is shown on the graph as the sloping red line. Over the flow range used to calculate the uncertainties, the meter factor changes of the order of 2-3 per cent.

Note that the inner blue lines are the 95% confidence limits for the linear meter factor fit and the outer, that for the mean meter factor.

The headline uncertainty for Probe B's performance uncertainty, shown in table 5.15 and normalised to the median WISPY meter flowrate of 65.5l/s is $\pm 2.77\%$. However, outside the 15-100 l/sec window of the calibration test schedule the probe meter factor will be increased, in line with the form of the linear meter factor fit. Thus, the $\pm 2.77\%$ uncertainty for probe B's calibration, shown in table 5.15, must be taken in context with the range of flows for which the uncertainty has been calculated.

For the mean meter factor fit, (Appendix 8) the statistical calculation gives a value of $\pm 9.03\%$, over the stated 15 - 100l/s flow range. This indicates the importance of understanding the statistical basis for describing the battery EFM performance when applying the probe to practical applications. The value of repeated test points is also very helpful in providing sound statistical data.

Refer to figure 5.36 which shows probe B's calibration one year later and where the finding, listed in table 5.15, is that the linear-fit meter factor has changed by 1.7%.

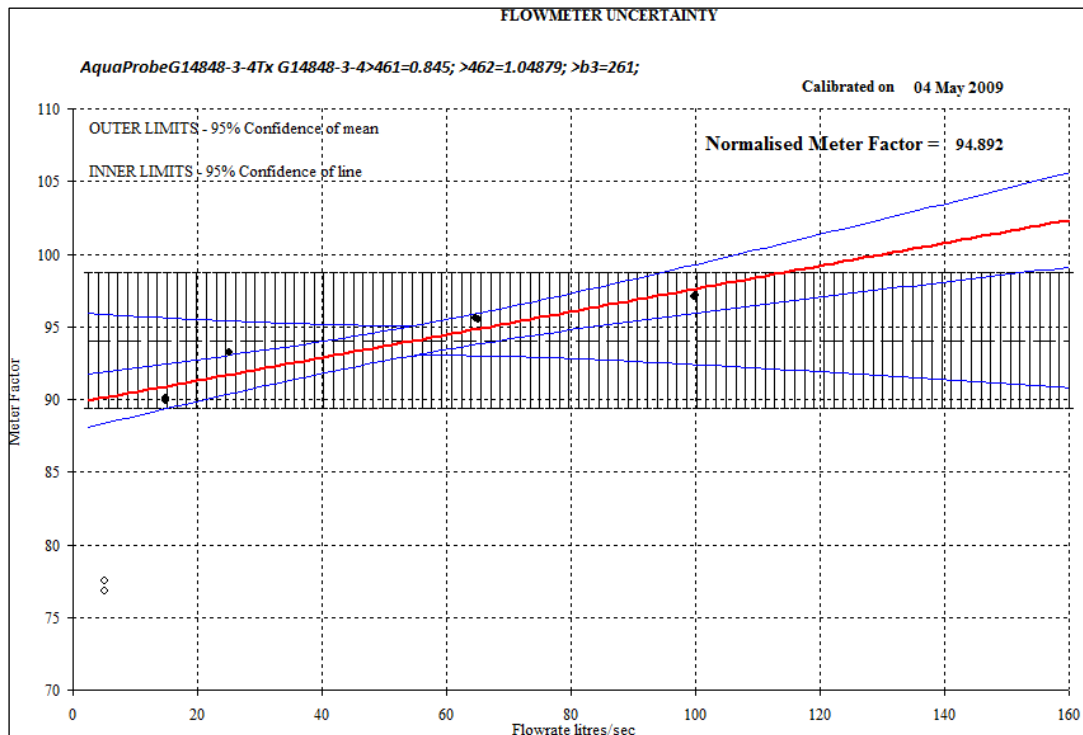


Figure 5.36: Flow meter uncertainty for Probe B, 2009-08-18

The item of note concerns the change in the EFM probe performance at the lower flows, where the meter factor is significantly different under lower velocity conditions - approximately 0.1m/sec. Nevertheless, probe B still shows good reproducibility at 0.3 m/sec and higher.

Over the year, the linear-fit MF factor has fallen -1.7% but the central uncertainty fit is little changed at 3.44%; +0.67% above the previous year's value. When the mean-fit meter factor is calculated, the change is only -0.3% year on year, but with an uncertainty which has increased from $\pm 9.03\%$ to 12.25% .

Details of the change in probe calibration factors.

The statistics for the change in probe calibration factors over the year, including probe B, are shown in figure 5.37 which plots the change in both meter factor formats, linear-fit and mean-fit, one year apart.

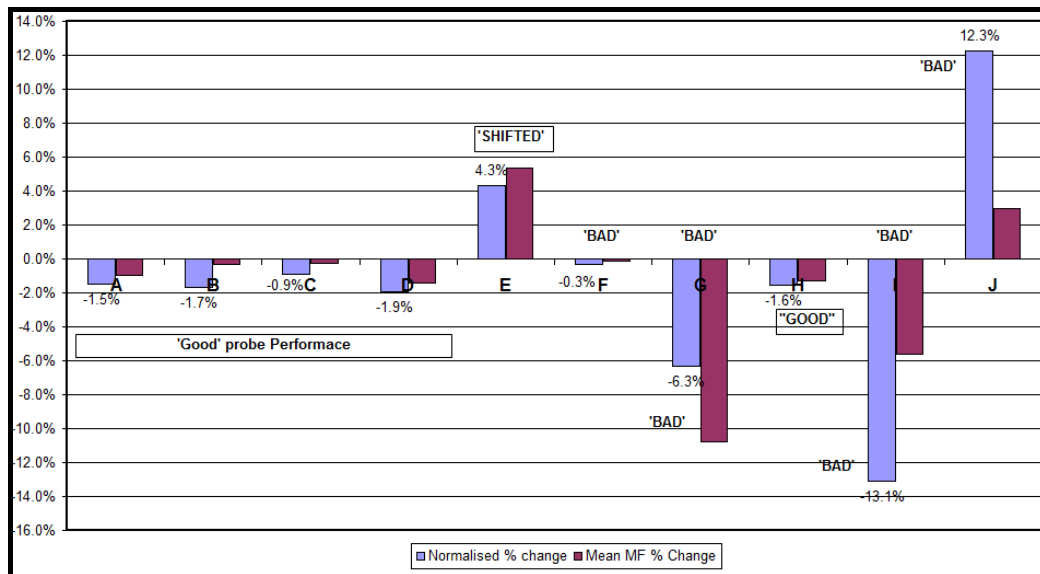


Figure 5.37: 1-year % change in probe calibration factors

The probes are arbitrarily labelled ‘good’, ‘bad’ or ‘shifted’, as judged by the results in table 5.15. However, a result of particular interest is that for probe F which superficially appears to perform acceptably and would not be labelled “bad” on the basis of the numerical performance assessment.

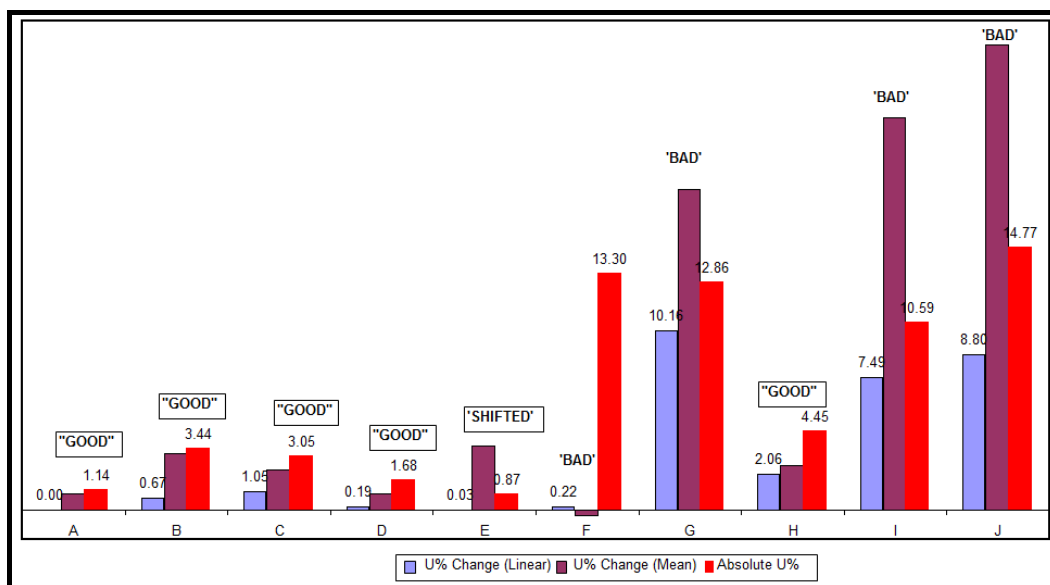


Figure 5.38: Plot of uncertainty change in meter factor

Figure 5.38 above plots the change in uncertainty for MF, rather than the change in the meter factor alone. Probe F appears to have an acceptable performance. If, however, rather than examining the relative change one looks at the absolute value of uncertainty, it becomes apparent that probe F is not acceptable. This is illustrated in probe F’s individual calibration result shown in figure 5.39.

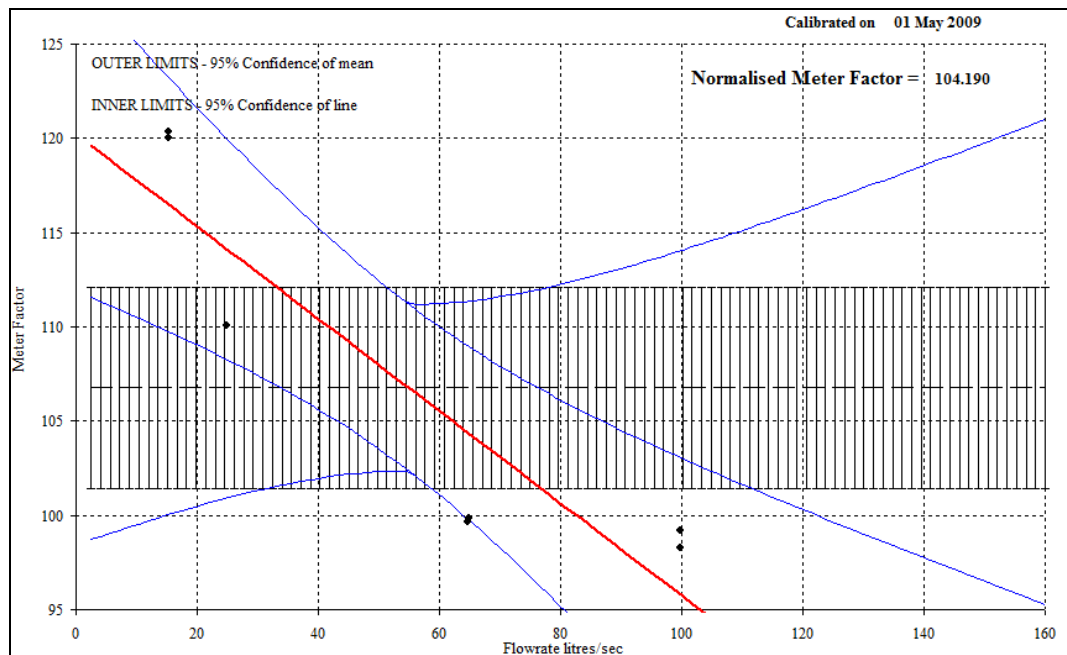


Figure 5.39: Probe F calibration characteristic – ‘Bad’

The error characteristic, like other probes exhibiting poor performance, shows a reversed relationship between MF and flowrate with MF decreasing as the flow increases. Also, the spread in MF over the test flow range is excessive, from below 100 to above 120. Nevertheless, the averaged data is such that the probe appears not to have shifted.

The conclusion reached after reviewing the one year recalibration results for a batch of ex-service battery EFM probes is that when assessing and categorising the performance of any particular instrument, it is essential to examine not only the numerical statistics deriving from the calibration but also the shape and form of the characteristic.

5.8 BENCHMARKING OF ACHIEVABLE METER VERIFICATION PERFORMANCE WHEN USING A BATTERY EMF PROBE

The description of the development of automated profiling and verification software is covered elsewhere in the thesis. However, following determination of the laboratory reference pipework profile factor and the standardisation of a probe calibration methodology it was decided to benchmark the level of performance which could be achieved when verifying a full bore meter using a battery EFM probe; under ideal conditions in the laboratory.

This exercise directly addressed certain stated aims of the thesis, which are to investigate the performance, limitations and use of the battery EFM probe as a profiling/meter verification device.

To undertake the exercise a variant to the AutoProfile profiling software, AutoVerification was created. This allows the process of data acquisition to continue

after the profiling exercise had been completed and enables the verification of a meter which is in line with the flow being measured by the probe.

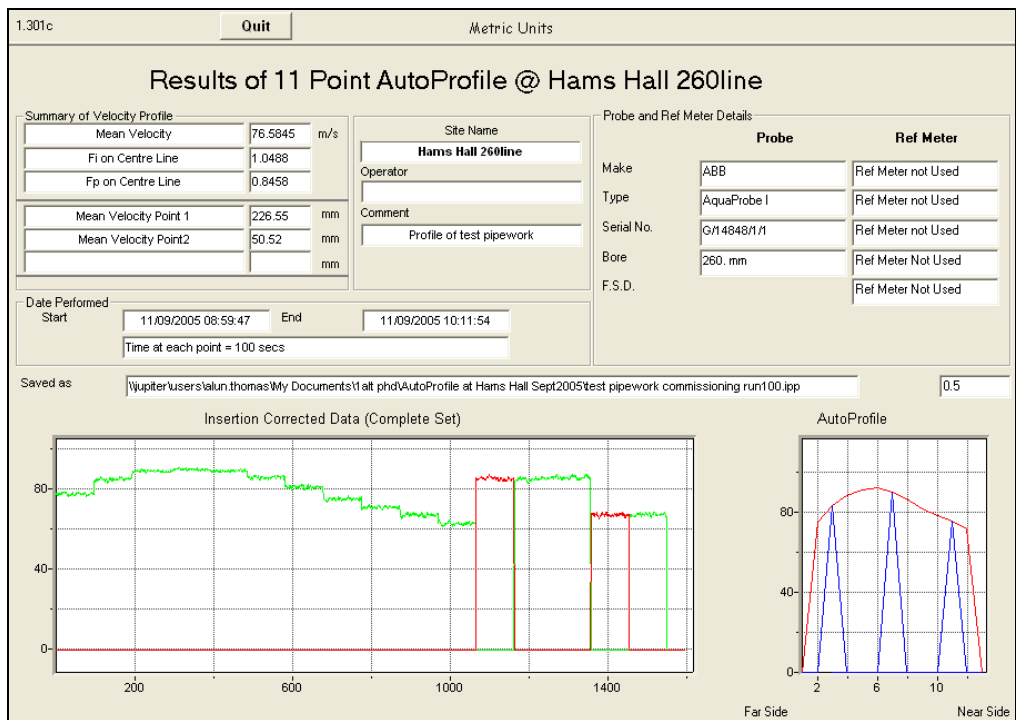


Figure 5.40: AutoProfile forming part 1 of the meter verification test, 11Sept05

Figure 5.40 shows the AutoProfile determination of the reference section profile factor immediately prior to the meter verification. This measurement is then followed, without moving the probe in any way, by the verification itself.

Figure 5.41 shows a screen shot of the verification element of the software which returns the value of the integrated probe flow as measured against the in-line meter under test (MUT). In this particular case the MUT is the UKAS calibrated IPTS digital master meter.

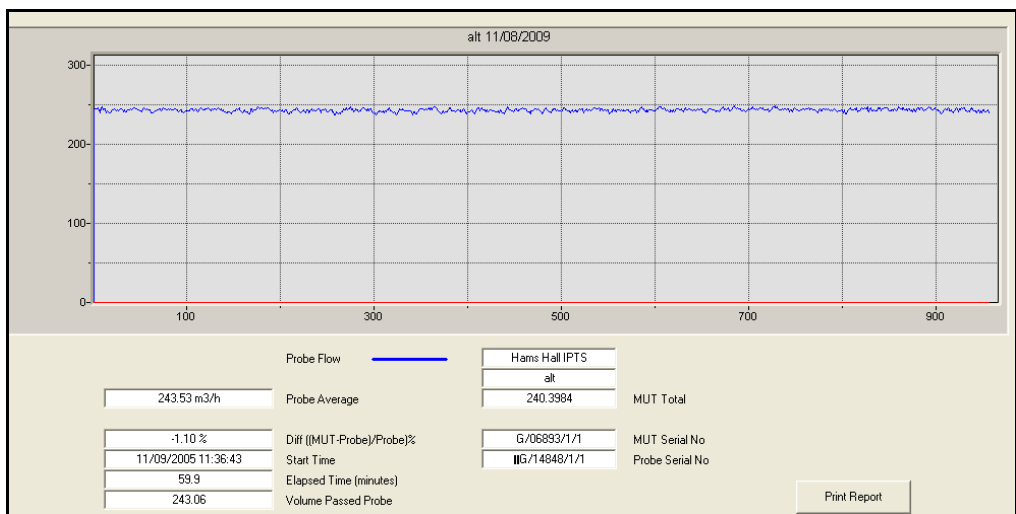


Figure 5.41: AutoVerification screen forming part 2 of the meter verification test, 11Sept05

The value of F_p calculated by AutoProfile, prior to starting the meter verification, was 0.8458. This is 0.3% lower than the averaged beam pitot result. Over the nominal hour period of the meter verification the digital flowrates of both the probe and the master meter were logged by the software. For the probe this volume totalled 243.06m^3 over the test period and for the IPTS master meter volume, 240.3984m^3 .

The difference between the meter under verification and the probe was therefore minus (-) 1.10% as measured over the test period, and can be read from the screen shot shown in figure 5.41.

Importantly this meter verification result lies within the 1.64% combined uncertainty of the probe, the velocity profile and the master meter. This figure was calculated referencing the following figures:

- (a) 0.85% from the uncertainty of the probe calibration, G14848/1/1
- (b) 1.4% from the uncertainty of the reference section profile factor, as derived using the beam pitot measurements and
- (c) 0.12% due to the uncertainty of the master meter calibration.

The benchmarking exercise therefore empirically demonstrated that when using a battery EFM probe one can, in conjunction with suitable software and under laboratory conditions return a value for meter verification which lies within $\pm 2\%$ and with an uncertainty of nominally $\pm 2\%$. This exercise therefore effectively defines a level of traceable performance against which regulatory policy may be set.

5.9 SUMMARY OF PROBE CALIBRATION AND RE-CALIBRATION FINDINGS

The generic conclusions from the probe calibration and re-calibration exercise are:

- (a) That it is important to regularly recalibrate battery EFM probe meters if they are to be used within the regulatory process with confidence. Specifically, at the end of one year's operational use one requires confidence that the probe results have not been shifted due to wear and tear.
- (b) That meters appear to fall into simple categories, i.e. good – retaining their characteristic; shifted – where the meter factor is observed to be radically changed; bad – where, gross changes $>5\%$ are evident.
- (c) That identifying a 'good' probe from a 'bad' probe, requires knowledge of both the change in meter factor **AND** the absolute value of the uncertainty. As probe F illustrates, small changes in meter factor may still mask a significant problem.
- (d) That for 'good' probes, year on year, meter-factor reproducibility has been shown as achieving better than 2%, with the average for the sample listed in table 5.13 of a 1.5% decrease.
- (e) That for 'good' battery EFM probes, the uncertainty associated with the linear meter factor calibration has been shown to average $\pm 2.36\%$, with a year on year difference change of 0.79%.
- (f) That the use of simple mean value meter factors is unwise and can mislead.

6. PROBE VELOCITY PROFILING AND METER VERIFICATION

OBJECTIVES

To improve the data collection and benchmark data quality from the battery insertion probe, in order to be able to investigate the performance and limitations of the meter when applied as a velocity profiling tool, forming part of the water industry's system of verifying regulatory water-into-supply (WISPY) meters.

To deliver this objective, and build an understanding of the practical detail when applying the battery insertion probe, required that work be advanced on four fronts.

1. The development of a data collection software tool which would improve the data quality and traceability of the velocity profiling technique;
2. Establishing the accuracy, reproducibility and qualitative performance of the verification technique, through measurement of baseline velocity profiles at Hams Hall and the probe manufacturer's production plant;
3. Conducting field trials with the developed software on representative WISPY sites
 - a. to discover weaknesses and sources of error when using the battery insertion probe meter.
 - b. to demonstrate and quantify field probe profiling verification performance; probe limitations; achievable data quality; and operator process improvements.
4. Investigating the limitations of the probe in respect of vibration when profiling, with emphasis on verification in larger pipe sizes, >400mm or at higher velocities, >1.5m/s.

6.1 DEVELOPMENT OF AN ENVIRONMENT AGENCY COMPLIANT PROFILING/VERIFICATION SOFTWARE APPLICATION

6.1.1 Overview of profiling/verification software scope.

Past practice for meter verification using insertion meters involved a series of separate, mixed paper and electronic records, followed by additional off-site data analysis to compare the probe and the meter under test.

An integrated, software based design offered improvements where the fundamental time series recorded data, the data analysis and the database archive could be integrated. Creation of an integrated design would provide clear evidence of the state of the on-site flows being measured as well as facilitating subsequent examination by engineers, managers and administrators forming parts of the regulatory reporting chain.

An additional advantage of this approach is that it can allow the present two part verification process to be concatenated into a single site operation. Thus one could first conduct the profile at the test location, then follow it immediately with the assessment of the meter under test, with all actions and logged data being processed and archived by the same routine.

6.1.2 Current position re regulatory verification data collection.

Prior to this work, the method of collecting data adopted throughout the water industry had been by use of purpose designed but physically separate dataloggers connected to the output of the insertion flow meter which is placed in line with the meter under test, often called the “station meter”. Such data collection is ‘blind’, providing no feedback to the user during the progress of the on-site work. In particular there is no visual representation of the live measurements from the insertion instrument and no collection of time series rate based data. This makes quality assurance of the data very difficult as the operator is unable to observe the data being collected and has no interactive power to intervene and remove unrepresentative data.

The quality of past data has thus been variable, and the investment of site technician resources, on-site, has to date always been undermined by an inability to assess data collection performance quality, due to a lack of appropriate on-site analysis tools.

This has consequences in terms of regulatory control with regard to audit and accuracy checking, as neither can the complete time-series source data be made available easily, nor can the technician control the active on-site process to try to deliver results which are known to be representative.

6.1.3 Generic profiling/verification software requirement challenges

Building on the known list of potential sources of error contributing to the measurement of velocity profile [78], together with operational weaknesses [77] a joint requirements statement was created with the Environment Agency (EA)[79]. The aim of this statement was to guide the proposed software development, eliminating or minimising the current problems associated with verification.

The wording read as follows:

that in respect of the verification of meters and/or the derivation of site velocity profiles, the process shall require:

- | | |
|--|--------------------------------|
| 1) the collection of traceable evidence, | which is |
| 2) accurately collected, | by competent trained Personnel |
| | using |
| 3) independently calibrated equipment, | to create a |
| 4) verification record database, | which can be |
| 5) objectively analysed, | and |
| 6) categorised using uncertainty techniques, | and |
| 7) securely archived, | to achieve a single |
| 8) metering installation uncertainty, | which can be subject to |
| 9) periodic, independent review. | |

To deliver an accurate profile involves measuring the velocity at a given number of points across the diameter of the pipe, and calculating the mean velocity using one of a number of standardised methods [35]. Once the mean velocity is known then the profile factor, F_p , stating the relationship between the centre line and the mean velocity can be found.

Four general methods of determining F_p have been used within the water industry, namely (i) the equal annular area method, (ii) the log-lin method, (iii) the log Tchebycheff method and, (iv) the method of cubics, with past choices typically reflecting ease of computation. Modern computing power has removed such limitations and, because of its flexibility, the method of cubics is now widely adopted as the calculation method of choice.

Once the number of profile points and their locations has been set, the task is to locate the measuring probe accurately and measure the point velocities. In the laboratory environment it may be possible to control the flow and to distinguish small differences in flow velocity. On-site there is no control and the site technician is faced with the difficulty of establishing whether the data he has collected is representative of the flow velocity distribution within the pipe, or possibly an anomalous record due to unrelated influences.

The ability of an operator to distinguish, on-site, atypical events from those thought to be representative, is key to the provision of improving the quality of the data collected. With current water industry procedures, generally modelled on advice from the manufacturer, a technician has no way of assessing the data until he is back in the office. Irrespective of the probe performance, calibration or traceability this weakness was identified as representing a significant limitation to the application of the technique.

6.1.4 Profiling/verification software design principles.

In response to the above, a strategy was developed to integrate the separate elements of the profiling and meter verification tasks into single integrated, software driven process. The process comprised six principle themes:

- (i) to collect digital, time-series data, direct from the insertion probe and the meter under test, i.e. to use RS232 comms, where available;
- (ii) to make the data collected available to the operator in real time, with statistical descriptions, for real time decision making, i.e. to graph the data as it is collected, value by value and to present the operator with statistical descriptions of the data being measured;
- (iii) to minimise the need for post processing by storing all data, enabling audit at a later date, i.e. to pass all real-time data into a database;
- (iv) to provide the ability for the field technician to repeat and change the profile sequence on-site by being able to retest and re evaluate measured points, i.e. to make the profiling process interactive, not passive;
- (v) to provide secure data archiving, including all the instrument, site and operator details, i.e. to eliminate pieces of paper, notes, etc and to digitally extract instrument setup information as part of the process;
- (vi) to design for the normalising of profile data with changing flowrate through use of the meter under test as a reference.

A flow diagram outlining the profiling software developed in line with these principles is shown in figure 6.1. Although sharing use of automated profile calculation elements, described by Herne-Smith [76] the focus in this development was process and quality related to better underpin regulatory policy.

Flow Diagram

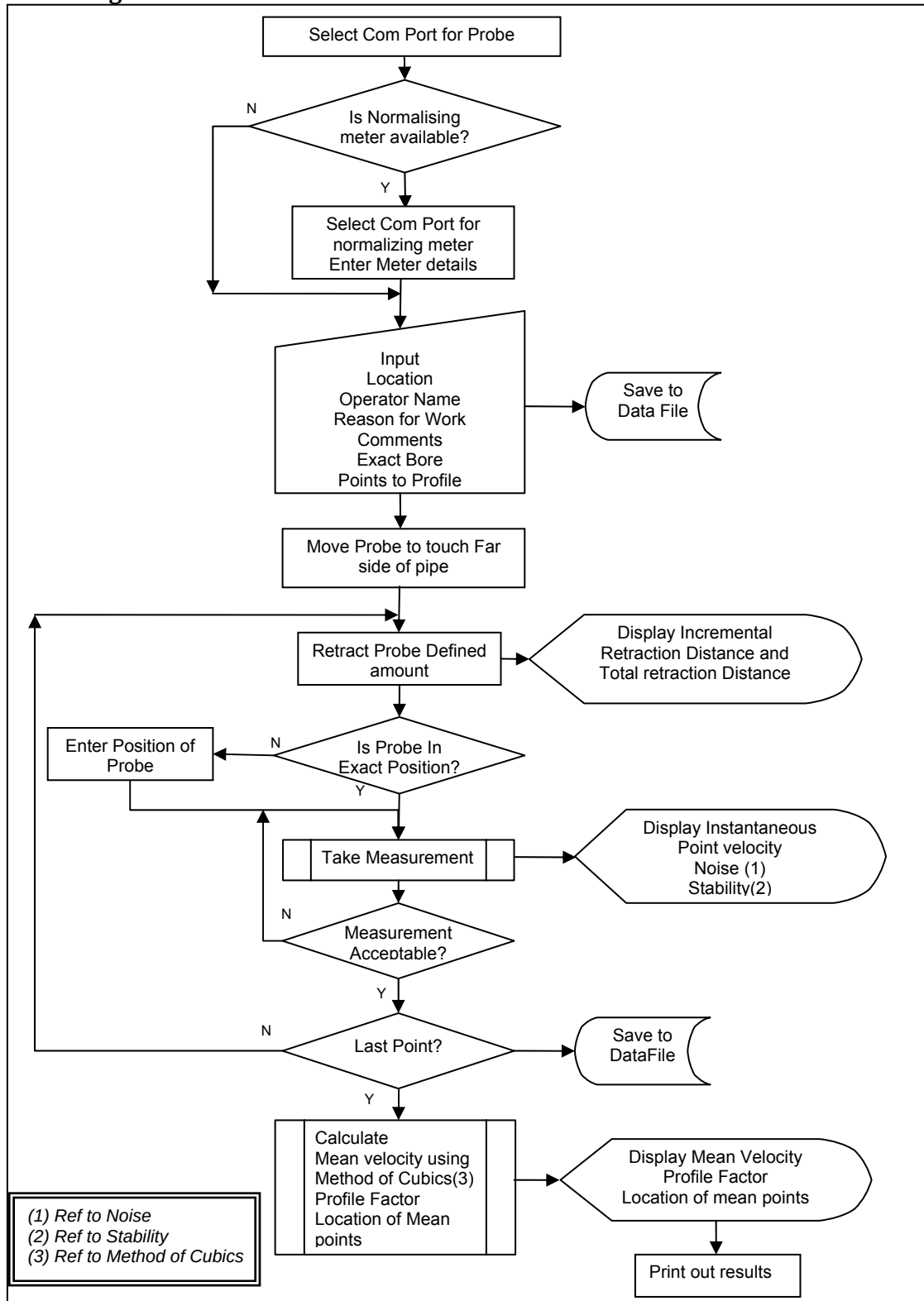


Figure 6.1: Flow Diagram of Profiling Software

6.1.5 Using the developed profiling/verification software package

The utility of the software lies in providing improved traceability of the profile measurements and in combining what previously had been separate activities of profiling and verification. Specifically, it is designed (a) to address the administrative demands of good record keeping required by the EA and (b) to guide the site technician through the process of automatically measuring the velocity profile, interactively allowing for repeat measurements and corrections as necessary.

Two operational implementations of the code were developed, one to address standalone probe profiling use, the other to support profiling where normalisation for flow changes is possible by utilising flow data imported from a separate reference or master meter.

Scope of site information input by the operator.

The profiling sequence is fully controlled through the software. It begins by automatically requesting information related to the comms ports to which the probe and, if available, the meter under test are connected. Once digital RS232 communications are established, interrogation of internal meter setup parameters as well as the recording of the digital flow data can be actioned.

The second tier of information requested by the software relates to the 'who, what where and why' aspects which the EA require to traceably administer the test. Prompts ask for (i) the location; (ii) the operator name; (iii) the reason for the work and (iv) comments related to the test.

The operator must next (v) enter an exact, not estimated, size for the pipe. He must then (vi) enter the number of profile points to be measured which must be an odd number between 7 and 29 and finally, (vii) the time to measure at each point. A default of 20 seconds minimum is set to ensure that the operator cannot unduly shorten the logging period over which individual point velocity measurements are made. In practice 20seconds nominally corresponds to recording 20 data points.

When all the data has been entered a window will open which will allow the selection of a name for the data file and a location to store it in. When the name has been accepted, a number of information boxes are displayed indicating the tasks being performed by the software followed by the appearance of the main measurement screen.

Method to prompt probe position for improved profiling.

Following input of the essential site input information the program commands the technician in the required actions regarding sequential positioning of the probe e.g. move to far side of pipe; retract by 26mm etc.

When being instructed to move the probe, the information box on the screen shows the technician two measurements, the distance to retract for that particular positional change and the total retraction distance achieved so far. In the first movement these two measurements will always be the same, but in subsequent movements, the total retraction distance will be incremented by the retraction distance of that point.

In many instances on site it is very difficult to accurately position the probe at the exact point requested by the integration algorithm e.g. 123.1mm. The software design acknowledges this by first instructing the technician regarding where to place the probe, then asking if the probe is in that exact location. If not, the software allows the technician to input to the screen the actual position which has been achieved e.g. 125mm not 123.1mm. In this manner the values which the method of cubics integration program processes are true. This correction facility ensures that the calculated profile is devoid of the potential uncertainties present in alternative manual or semi-manual methods.

Capability to compensate for flow variations during testing.

The profile measurement screen is designed to show three graphs, one for the instantaneous probe data, one for the instantaneous master meter data – where available - and the third to display the profile as it develops. In this manner the active involvement of the technician is maintained and the progress of the test visualised. This is important as it shows the shape of the profile as the process develops. This provides the operator with knowledge which previously has not been available until post processing of the data off-site. It is key to providing feedback to allow the operator make judgements about the validity of the profiling exercise, as it progresses.

Live operator interaction: display of digital data and profile information.

All communications with the probe and master meter are through RS232 links so that asynchronous digital readings, direct from the meter processor, form the archived record. As these measurements are sent from the probe/master meter they are both archived in the database and displayed simultaneously, all in real time. At the end of the individual profile point, the graph headed “raw data” is added to the screen. This shows the velocity figures plotted against the pipe diameter, corrected using the manufacturer’s insertion factor which compensates for the probe position.

Following completion of the full number of traverse points a graphic of the full profile is placed on the screen. A prompt, the option to check three check points is offered as a means of positively demonstrating that the flow has not changed significantly. These points include the second in the profile sequence, that on the centre line and the penultimate point in the traverse. Recording of these three points thus visually establishes the reproducibility of the profile over the period of the test.

At the end of the profile a summary profile graphic, complete with repeated points plus the site details, computed statistics and detailed visual plot of the recorded data is displayed.

Live data quality assurance by the operator.

For all data received, at the end of each profile point a tick or cross will appear on screen for the two inbuilt data assessment values; “noise” and “stability”. The software thus makes a recommendation to the technician as to whether the measurement is within limits or not and it is the technician who decides whether to accept or reject the measurement.

The “noise” and “stability” are computed against inbuilt limit criteria using the data collected during the specific run. “noise” is defined as the difference between the maximum and minimum probe velocity values, ratio’d to the computed average for the individual adapt run. i.e. “noise” = $((\text{maxread} - \text{minread}) / \text{averead})$. If “noise” > NoiseCheck , a fixed value pre-programmed into a separate location then a “reject” flag is raised and communicated to the site technician on screen.

For “stability” a variable Changeread is defined as equal to $(\text{LastFive} - \text{FirstFive}) * 100 / \text{FirstFive}$, hence creating a value whose size indicates the change in data between the start and end of the sample period. The Pass/Reject limit for Changeread is set relative to the value pre programmed into a separate variable called Slopecheck. Should Changeread exceed Slopecheck then a “reject” flag is raised and communicated to the site technician.

A third test on the data collected during profiling is calculated. It is defined as “reproducibility” and is used to assess the change in measured centre line profile velocity over the period of the test. It is equal to the absolute value of the difference between second check velocity measurement and the initial measurement. If this figure exceeds the value pre programmed for the “stabilitycheck” variable then a “reject” flag is raised against “reproducibility” and shown on the operator’s display.

The default settings which set the displayed operator advisory “pass/reject” display settings are:

NoiseCheck = 0.5	50% change in the variable over the test period
SlopeCheck = 5	5% change in the variable over the test period
StabilityCheck = 0.1	10% change in the variable over the test period

Nevertheless, the “accept” or “reject” option is a recommendation and can be overridden by the technician. If data is rejected then it will be necessary (compulsory) to take the measurement again. When the measurement is accepted, the software resumes the planned sequence with an instruction to move the probe again.

Where data is rejected it is not permanently deleted from the record but forms a part of the archive, being highlighted for easy recognition. This is a key design feature and formed one of the principle requirements specified by the Environment Agency. It ensures that for an external audit that there is no question of the operator hiding or deleting inconvenient or “bad” data. In particular, it allows one to observe whether the technician has achieved a satisfactory result by multiple retries, rather than with a single run.

Site profiling integrated with meter verification

Once the site profile has been established in a form that allows the quality of the measurement to be established and recorded, the software offers the opportunity to proceed to verification of the meter under test. In a similar way to the above, the package allows the meter that is to be verified to be recorded in parallel with the probe insertion flow meter for a predetermined period of time. All time series data from both

instruments is visible to the operator and real-time results are stored in the database for subsequent post processing.

Inbuilt to the software are serial communications which for known meter models can automatically interrogate the respective electronic transmitters and hence effect different modes of probe/meter operation may be selected.

All meter actions are recorded, ensuring that the quality, visibility and traceability of meter data, including the electronic transmitter set-up parameter used at the time of the test are auditable.

6.1.6 Regulatory advantages delivered by the profiling/verification software

Prior to the development of the software the data quality of a site profile was assumed to be good when the shape of the profile met prior expectations. This hid the reality that, because there was no collection of time series data, the results were essentially low pass filtered “guestimates” based on average spot readings “eyeballed” by the on-site technician. Such results are of unknown quality.

Due to the absence of direct pressure from the regulator to demonstrate data quality and traceability, influence factors such flow perturbations and drift in the bulk flow during a profile were necessarily unconsidered.

With the development of this software featuring logged, visual, real-time, digital data, achieved performance can not only be retrospectively demonstrated but the individual site characteristics can be quantified by way of ancillary generated statistics.

The method thus improves reporting quality and may, by providing statistical descriptions of the recorded data, lower the overall result uncertainty which can be legitimately claimed.

From the regulatory position, the software delivers certitude through traceability, supported by the four key attributes of increased –

- Precision: the base data forms a true time series record of point velocities;
- Visibility: perturbations can be ‘seen’ visually on screen and addressed by the operator on-site as part of the profiling procedure;
- Rigour: through applying a standardised integration method linked to ancillary algorithms which can describe data quality in real-time;
- Quality: achieved by eliminating the need for user expertise in the process; by standardising the procedure; by guiding the process; by using real-time digital data; and by providing operator feedback in real-time.

6.2 ESTABLISHMENT OF LABORATORY PROFILING PERFORMANCE

6.2.1 Objective of the profiling exercises

The purpose of undertaking a series of profiling exercises was to establish the accuracy, reproducibility and quantitative performance of the probe profiling technique, through

measurement of baseline velocity profiles at Hams Hall and the probe manufacturer's production plant.

The objective was to assemble, under laboratory conditions, key performance information (KPI) to describe and quantify the achievable quality of the battery insertion meter profiles which form the basis of the regulatory WISPY meter verifications. The KPI format could then be used to comparatively assess the results being obtained from different water-into-supply sites.

6.2.2 Hams Hall test schedule and methodology

The profiling exercises conducted at Hams Hall consisted of a series of five discrete tests starting in October 2006 and ending in January 2007. The data collected was recorded using the developed profiling software.

The first three tests were made in October 2006 and aimed

1. to establish the generic repeatability and reproducibility for profiling in the laboratory; initially using the same probe and utilising the developed profiling software;
2. to generate sufficient data for subsequent analysis and to enable development of representative KPI's.

Further tests were made in December 2006 and January 2007 and were targeted on gathering results with different probes, with a view to encompassing any additional increase in uncertainty which the use of alternative measurement equipment might introduce. This was planned to mimic the situation in the field where contractors routinely use different probes when repeating profiles.

The scope of the analysis was set by the standard descriptions programmed into the profiling package. To this were added additional statistics to encompass data quality and uncertainty. The list of data descriptors applied for analysing the results are as follows:

- a) NSE, normalised standard error: the ratio between the standard deviation of the dataset and its mean value. Effectively a measure of the spread of the sample.
- b) NSE, but ratio'd relative to the value on the pipe centre line to highlight asymmetry
- c) noise, as previously defined in the profiling software description.
- d) stability, as previously defined in the profiling software description
- e) reproducibility, as previously defined in the profiling software description
- f) expanded uncertainty, equally to twice the NSE
- g) variable expanded uncertainty; a modified form of expanded uncertainty to allow for low pass filtering introduced by smoothing factors programmed into a transmitter.

6.2.3 Asymmetry of the insertion probe measured Hams Hall profile

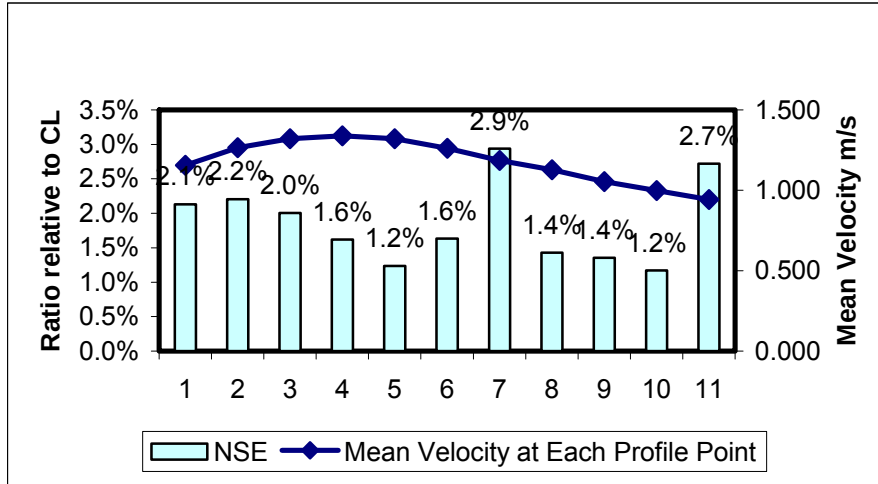


Figure 6.2: NSE plus mean velocity at each profile point; vertical plane

The profile in figure 6.2 is seen to be apparently asymmetric, yet with a only small element of the skew being attributable to imperfect hydraulics; reference the beam pitot results - chapter 5, figure 5.9. The major contribution of the observed skew is generated as part of the profile calculation and is due to the deliberate corrections made by the manufacturer to the measured, raw, point velocities. These corrections stem from the requirement to adjust the raw data according to how far the probe is inserted into the pipe. They are intended to compensate for the so called blockage effect which the probe stem has on the bulk flow as it is inserted into the pipe. The corrections are effected using F_i , the manufacturer's probe insertion factor. F_i is directly linked to the insertion depth and is an intrinsic element in the manufacturer's formal application advice when deploying the insertion probe. It applies to all users.

Therefore, an important question to be answered in the context of setting probe baseline performance was how much would the skew, introduced by F_i in order to try to correct for local hydraulic distortion, contribute to inaccuracies in the true value returned for the profile factor, F_p ? Alternatively stated, what effect does the skewness introduced by the manufacturer's application advice have on the absolute value of the profile factor?

6.2.4 Profile factor sensitivity re measured profile skewness

The form of the probe insertion factor, F_i [80] derived empirically by the manufacturer comprises two elements. It is as follows:

$$F_i = \frac{1}{1 - \frac{2d}{\pi D}} + K \sqrt{\frac{2d}{\pi D}} \cdot \left(1 - \frac{2y}{D}\right) \quad \text{Equation 6.1}$$

With d = diameter of the insertion probe; D = diameter of the pipe (mm);
 $K=0.5$; and y = the probe insertion distance (mm)

It may alternatively be expressed as the sum of two elements, one a centre line component $F_i(cl)$, the other an off centre component $F_i(y)$.

$$F_i = F_i(cl) + KF_i(y) \quad \text{Equation 6.2}$$

In this format the value of K, set to 0.5 by the manufacturer, may be varied to explore the relative importance of the centre line and off centre components. It should be noted that this equation was created by the manufacturer and is empirically based.

When deriving the profile factor, F_p , the developed software needs to use two corrections:

- (1) that of the manufacturer's insertion factor, F_i , applied according to the position of the probe within the pipe to correct the measured point velocity and
- (2) “m”, a coefficient depending on the wall roughness and flow conditions, which lies between 4 (rough wall, low Reynolds numbers) and 14 (smooth wall, high Reynolds numbers [33]). According to FLOMIC it can be related to Reynolds number by $Re = (80,230 \cdot m^2 - 742,000 \cdot m + 1405,400)$ [64].

To explore the sensitivity of the manufacturer's insertion factor a profile of the Hams Hall line was undertaken inputting the de-facto standard value of $m=7$. Note that this was not exact as calculation indicated that for the particular test flowrate the true value of “m” which matched the Reynolds number of 328,000 should be closer to 7.45 and not the 7.00 input to the software.

Using this measured data which is automatically stored by the profiling program, K was varied from 0.5 to 1.0. This changes the off-centre line component of the manufacturer's insertion factor formula, thereby altering the correction of the point velocities distributed across the profile traverse and hence the apparent skew of the profile. Shown below are the screen shots from the software program illustrating how the profile shape changed as K was altered.

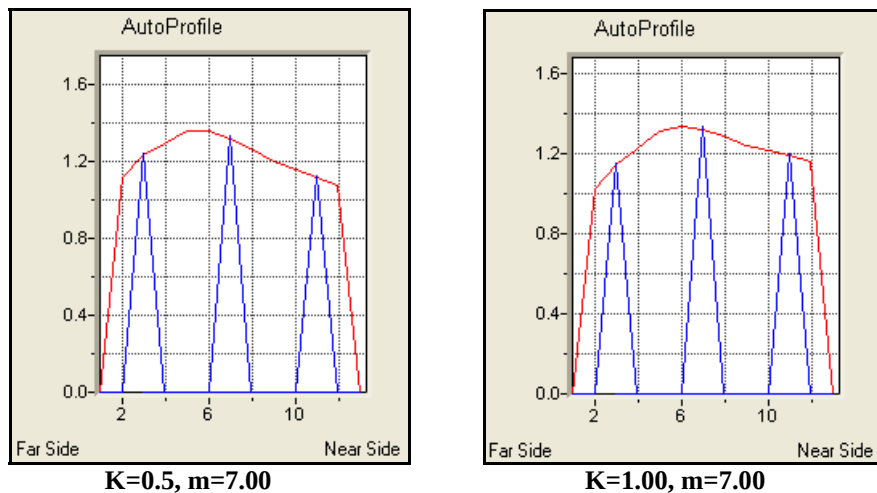


Figure 6.3: Profiling software screenshots: Hams Hall 260mm line; vertical plane

As can be observed, the degree of asymmetry has been altered but not eliminated.

The screen shots which now follow provide, for the same data, the calculated values of velocity and mean velocity position with $K=0.5$ to 1.0 . Note that the magnitude of the effect which the changes in K effected for the calculated mean velocity and profile factor are small, e.g. the change in F_p on the centre line is from 0.8466 to 0.8425 with the mean velocity changing from 1.1193 to 1.1138m/s – approximately 0.5%.

By contrast, the positions of the mean velocity point(s) were significantly changed by the changes to K. These points are often utilised by industry operators as an alternative to locating the probe on the centre line so that this result has considerable practical importance. This is illustrated by the screen shot values taken from the profiling software. Note the separate and individual sensitivity of the two calculated mean velocity points.

Summary of Velocity Profile			Site Name	
Mean Velocity	1.1193	m/s	Hams Hall 260line 19oct06	
Fi on Centre Line	1.0488		Operator	
Fp on Centre Line	0.8466		alt	
Mean Velocity Point 1	229.53	mm	Comment	
Mean Velocity Point2	43.52	mm	Profile prior to commencing probe cals 1	
		mm		
Date Performed				
Start	19/10/2006 10:23:48	End	19/10/2006 11:04:55	
Time at each point = 60 secs				

Figure 6.4: Summary profile for Hams Hall 260 line when K=0.5, m=7.00

Mean velocity Point1 changes by $(229.53 - 213.85) = 15.68\text{mm}$, as K ranges from 0.5 to 1.0, equivalent to a 12% positional change relative to the radius dimension.

Summary of Velocity Profile			Site Name	
Mean Velocity	1.1138	m/s	Hams Hall 260line 19oct06	
Fi on Centre Line	1.0488		Operator	
Fp on Centre Line	0.8425		alt	
Mean Velocity Point 1	42.51	mm	Comment	
Mean Velocity Point2	213.85	mm	Profile prior to commencing probe cals 1	
		mm		
Date Performed				
Start	19/10/2006 10:23:48	End	19/10/2006 11:04:55	
Time at each point = 60 secs				

Figure 6.5: Summary profile for Hams Hall 260 line when K=1.0, m=7.00

Whilst mean velocity point2 changes by $(43.53 - 42.51) = 1.02\text{mm}$, as K ranges from 0.5 to 1.0, equivalent to 0.78% positional change relative to the radius.

The juxtaposition of the calculated points indicates that the slope of the profile has moved across the centre line due to the variation in K. In addition note the high positional sensitivity of the mean point which is located on that side of the profile having the larger slope when K is altered.

6.2.5 Profile factor variation re Von Karman factor “m” and probe “K” factor
 Practical deployment of the profiling software necessitates the use of fixed values for both “m” and K. Of the two variables, “m” and K, it is the Von Karman factor “m” which has the greater level of uncertainty (a) because of differing values stated in the literature and (b) because of the difficulty with which it can be introduced

representatively when measuring across sites which have pipework whose internal condition may vary significantly.

Deployment of the developed profiling software therefore inherently introduces errors into the calculation of F_p from the inexactitude of the two factors. The graph below shows the size of these errors, displayed on a percentage basis related to the “standard” settings defined by $m=7.0$ and $K=0.5$. Data for the graph was obtained by running the profiling software program in its simulation, or specialist mode.

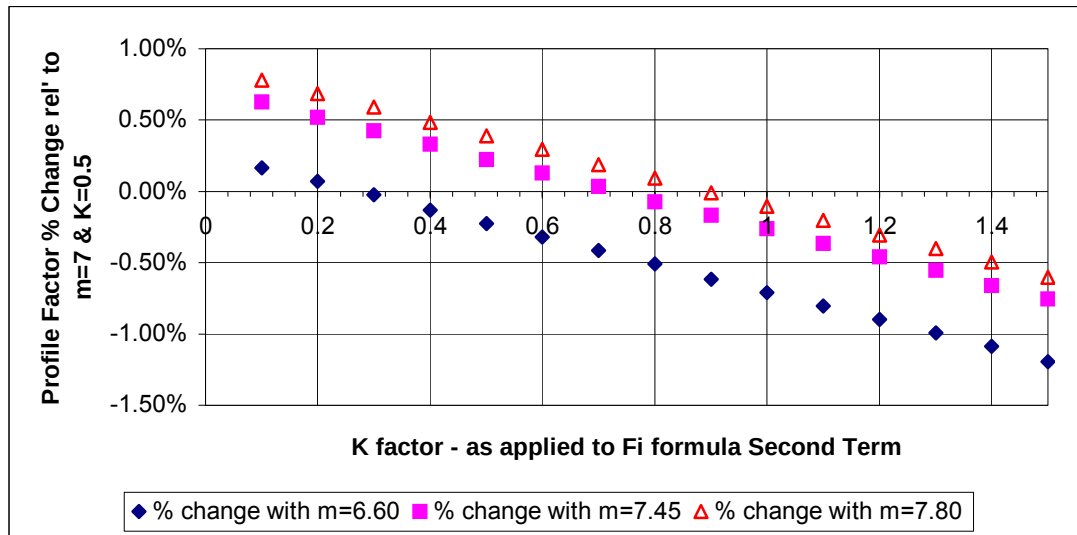


Figure 6.6: Hams Hall October 2006 profile factor percentage change due to “m” and K; rel’ to “m”, K=0.5 “standard” condition

In tabular form the limiting values are:

	m=6.6	m=7.45	m=7.80
K=0.5	-0.22%	+0.22%	+0.39%
K=1.0	-0.71%	-0.26%	-0.11%

Table 6.1: Limit values when varying “K” and “m” profile factors

They illustrate that for the possible range and combination of values of “m” and “K”, departing from the standard default values of $m=7.0$ and $K=0.5$ [80], causes a relatively small change to the calculated profile factor. Choosing $K=1$ as reference because it empirically showed a profile with optimum symmetry, the range of variation in percentage terms relative to the “standard” values is from -0.71% to -0.11%.

6.2.6 Measurement and discussion of laboratory profile reproducibility

A prerequisite to comparatively assessing individual measured profiles is the requirement to demonstrate the attainable level of reproducibility. A short program to investigate this level was therefore planned and the work was undertaken over a period of 12 weeks, including assembling, disassembling and reassembling the complete length of reference pipework.

Stability of the flow remained nominally unchanged from test to test, being disturbed only by oscillations in the line pressure set by the fixed speed of the pump(s) which are fed from the static head of the laboratory reservoir.

The chart below summarises the reproducibility results extracted from individual profiling tests where, at the end of the profile sequence, the operator is prompted to undertake a repeat of the three key velocity points; namely, the second point P2, the centre line and the penultimate point, P10 of the 11 point profile traverse.

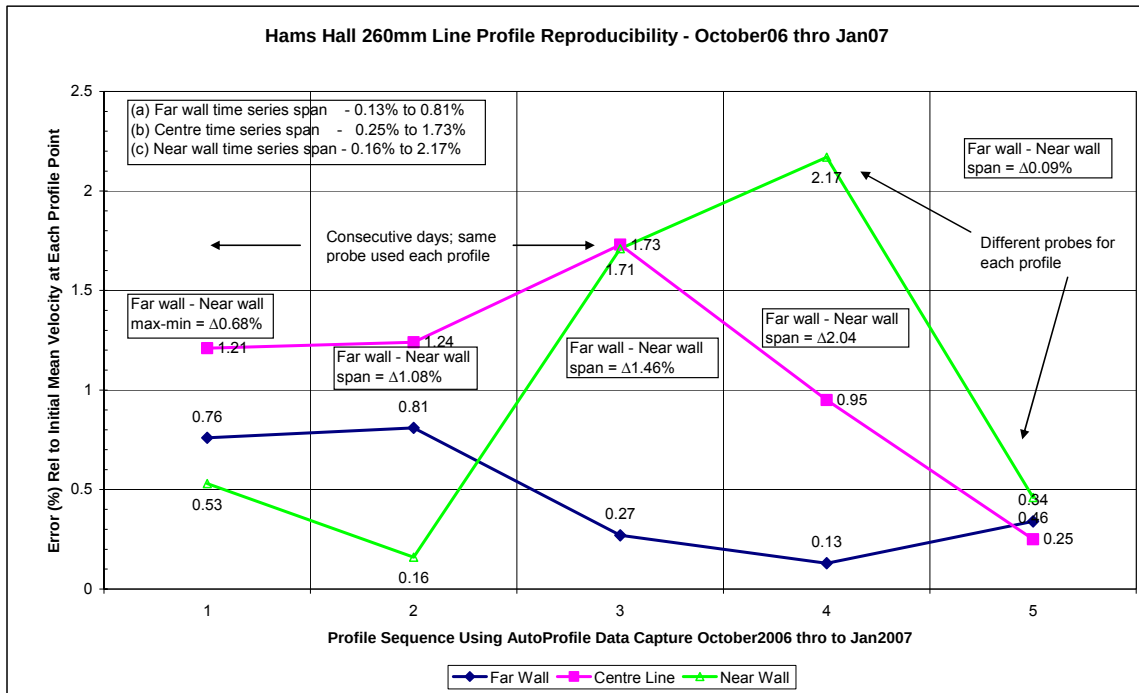


Figure 6.7: Hams Hall 260mm line profile reproducibility – October2006 to January2007

The graphed data represents the absolute differences between the initial and repeat measurements and is indicative of the representative range of values with which one could expect to measure the same point velocity within a nominally stable profile under optimal conditions. All the tests were measured at a nominal mean pipe velocity of 1.1m/s, 65.5l/sec. The second data set was an exception, being measured at a lower flowrate. Table 6.2 shows the spread of the repeated measurements for the four similar tests.

Nominal 65.5l/s in 260mm pipe	Span for all 3 repeat points (%)	Max of absolute point velocity % change	Min of absolute point velocity % change	Individual test profile factor Fp	% difference individual Fp relative to mean Fp all runs
19Oct06	$\Delta = 0.68$	1.21	0.53	0.8466	-0.29
20Oct06	$\Delta = 1.46$	1.73	0.27	0.8495	+0.05
15Dec06	$\Delta = 2.04$	2.17	0.13	0.8441	-0.59
14Jan07	$\Delta = 0.09$	0.34	0.25	0.8562	+0.84

Table 6.2: Hams Hall reference 260mm line; repeated point profile measurements

As can be seen the reproducibility of the point velocity measurements is good. Across all four tests the max – min percentage change encompassing all three repeat profile points, P2, P10 and the centre line is 2.04% (2.17% - 0.13%). For repeatability the best set of results was recorded during the January 2007 profile and achieved a span of 0.09%.

Overall, for the four profiles undertaken at nominally the same flowrate the span in Fp from the mean value of 0.8491 was from +0.84% to -0.59% i.e. better than +/-1%.

When the fifth profile, measured at a lesser nominal flow of 15l/s is taken into account the mean profile is lowered by 0.48% to 0.8450. The value of the low-flow Fp, which equalled 0.8286, is then -1.94% below the mean i.e. within 2%. Appendix 11 tabulates the data from all five trials.

6.2.7 Long term profile statistics and quality

The previous section, whilst carefully examining the measurement results for the bulk profile and profile reproducibility did not present information concerning the long term quality of the individual profile points. Understanding the long term data statistics is important because they illustrate the representative quality of the hydraulics at the particular measured location and require analysis of the individual profile paths and the time series data contained within each path. This is generally the form of analysis which is demanded when returning to a location over time in order to assess whether there have been significant changes in the local hydraulics. Thus, by examining the laboratory statistics it was the intention to establish a representative level of performance for near ideal conditions, against which field results could be compared.

Table 6.3 illustrates point velocity measurement performance against probe position with individual data statistics shown at each of the positions which make up a complete traverse of the pipe. A full analysis of the data can be found in [81]. Shortened observations are as follows.

	P1 230.00	P2 216.70	P3 194.70	P4 173.30	P5 151/6-	P6 130.00	P7 108.60	P8 86.90	P9 64.90	P10 43.30	P11 22.20	Mean of Means
Mean % Stability	-0.36%	-0.62%	-0.04%	-0.91%	-0.08%	-0.68%	0.16%	-1.72%	0.59%	-0.76%	-0.43%	-0.43%
Mean % Noise	11.11%	8.52%	7.10%	5.64%	5.70%	6.01%	8.90%	6.52%	7.47%	6.06%	10.04%	7.55%
Mean % NSE	2.40%	1.98%	1.67%	1.26%	1.26%	1.40%	1.98%	1.48%	1.56%	1.31%	2.22%	1.68%
Mean NSE relative to Centre Line	1.87	1.50	1.23	0.93	0.90	1.00	1.37	1.06	1.11	0.96	1.57	1.23
Mean % Reproducibility		0.47%				1.08%				1.01%		0.85%
Mean % Expanded Uncertainty	0.87%	0.72%	0.61%	0.45%	0.45%	0.51%	0.71%	0.52%	0.55%	0.47%	0.79%	0.61%

Table 6.3: Summary long term averaged KPI statistics Hams Hall 260mm reference profile line

Long term profile stability

The outcome of the five trials showed the stability of the laboratory tests to be high, with an overall mean of -0.43%, as shown in Table 6.3 above. However, for individual

tests the stability descriptor spanned +9.65% to -9.20%, even under laboratory conditions.

Long term profile noise

The utility of the noise statistic lies principally in being able to generate comparative values for an individual location and then to be able to contrast with previous tests.

At the beginning of the work there had been no indication as to what might be a reasonable expectation for noise. The testing measured an averaged figure of 7.55%, with a span of 11.1% to 5.6%. In terms of characterising data scatter this statistic may be referred to as being representative of laboratory conditions.

With regard to the positional distribution of noise, the evidence is that at the extremities of the profile, P1 and P11, one can legitimately expect to see a rise of the order of 2-3% over the average but that elsewhere, unless hydraulic disturbing forces are present, the noise should be expected to remain essentially steady.

Comparison between long term stability and noise

Figure 6.8 goes some way to demonstrating that, in the absence of imposed hydraulic energy such as found with swirl, the stability descriptor for a sampled profile dataset is independent of the noise.

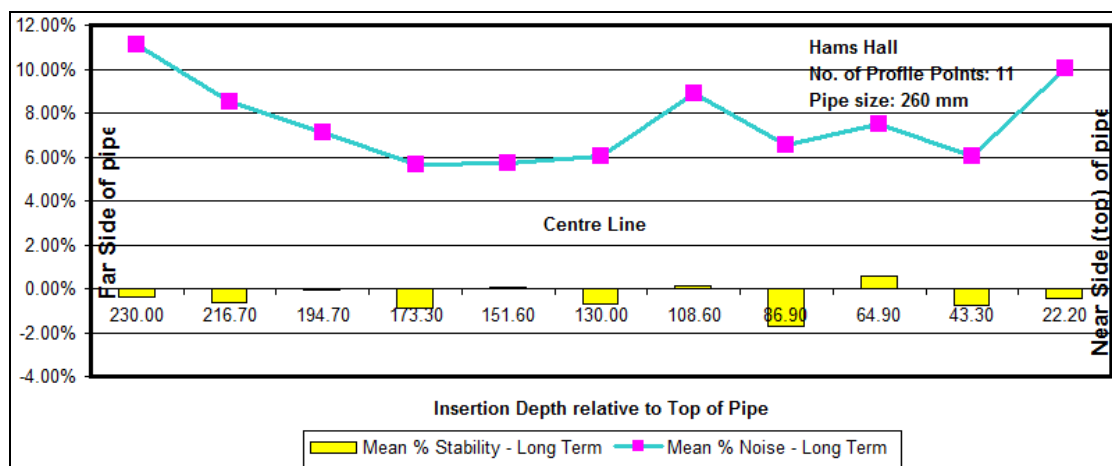


Figure 6.8: Long term Hams Hall averaged stability plus noise comparison

From this it can be seen that whilst the noise statistic is modestly related to position, with the data recorded nearer to the far wall being noisier than that from the near (top of pipe) position, the stability is positionally neutral within the bounds of experimental error.

Long term profile NSE

Key points are:

- that over the four-month period, the mean NSE value returned for all profile paths was 1.68%. This sets an expectation of what may be measured for data quality.
- that the limits of individual path NSE ranged between 2.40% and 1.26%, representing 42.9% through -25.0% around the mean.

(c) the centre line did not display the lowest NSE.

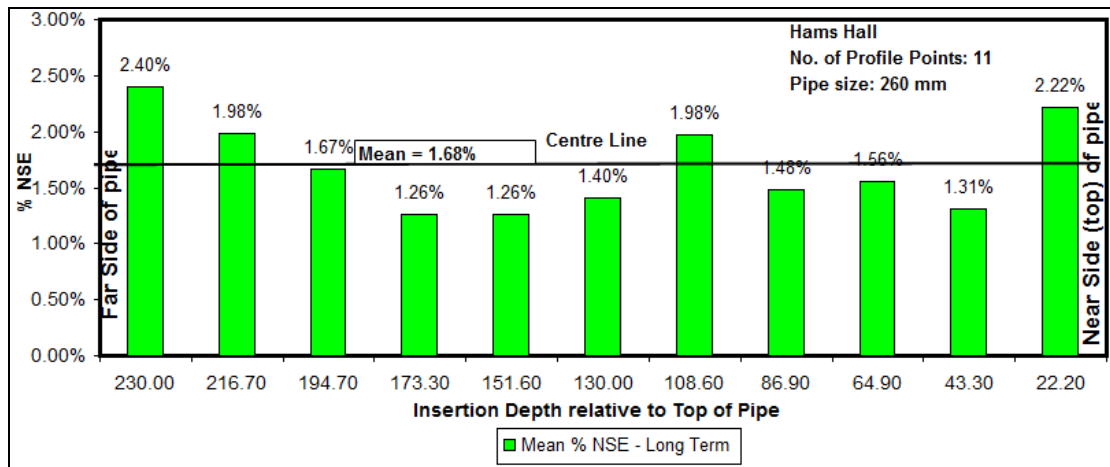


Figure 6.9: Long term Hams Hall averaged NSE comparison

- (d) That the quality of data, as described by the NSE statistic, can be seen to decrease as the probe moves towards the far wall, away from the centre of flow.
- (e) That at both outer profile points close to the pipe wall, the relative uncertainty rises significantly, indicating hydraulic interaction of the probe with the pipe wall.

Long term reproducibility comparison

Reproducibility is fundamental to establishing the validity of a profile. The Hams Hall laboratory results achieved excellent reproducibility, spanning from the worst individual result of +2.17% to the best result at 0.13%.

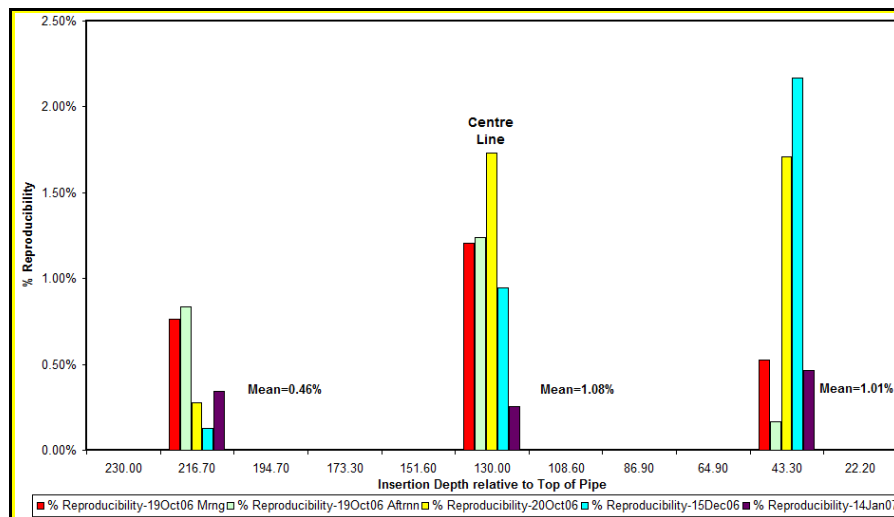


Figure 6.10: Long term reproducibility comparison

In context, these results reflect on the data collection methodology and technique which were successful in capturing representative datasets.

6.2.8 Profile tests at probe manufacturer, ABB Objectives

An obvious weakness in establishing the baseline statistical performance at only one laboratory is that pipe size, Reynolds number and flow conditions will be necessarily limited. To address this weakness the profiling exercise was extended to the probe manufacturer's plant under different but controlled hydraulic conditions. The aim was to compare and contrast the two sets of measurements as a prelude to site work using the developed profiling software.

Results of profiling ABB's factory 212mm probe production line

Appendix 12 tabulates the data from the tests undertaken on the production calibration line located within the manufacturer's factory. Detailed below are a series of graphs, together with a summary table comparing the Hams Hall and manufacturer results which have been generated from that data. The measured profile factor was 0.827 which contrasts with the theoretical value used by ABB of 0.850, a difference of -2.7%.

Figure 6.11 below shows the screen summary for the traverse on the 212mm diameter stainless steel 650B flow line. Note that the software had automatically rejected three of the runs due to exceedance of the predefined, internal check values, signalling a change in the conditions between the two locations.

During testing the flow rate was set so as to create a similar bulk flow velocity as that when profiling at Hams Hall, 1.22m/sec. This required the 212mm line to run at 43 l/sec, in contrast to the 65.5l/sec set flow at Hams Hall. The difference in Reynolds number was $Re = 257\,000$ at the manufacturer and $Re = 317\,000$ at Hams Hall; both at a nominal 20degC. The Reynolds number at Hams Hall is thus 23% higher.

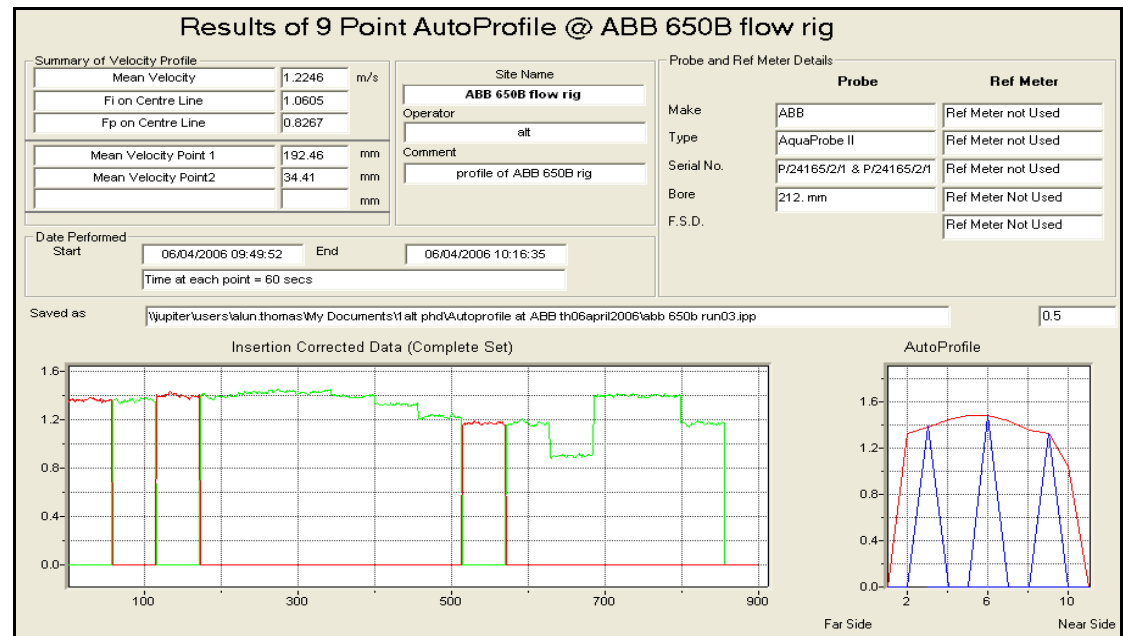


Figure 6.11: Profile of ABB's 212mm factory line

As shown, with F_p at 0.827, the 650B line shows a less flat profile compared to Hams Hall. The following graphs shows improved statistical descriptions for the profile data from the manufacturer's line, compared to at Hams Hall. There is one exception, NSE relative to centre line NSE.

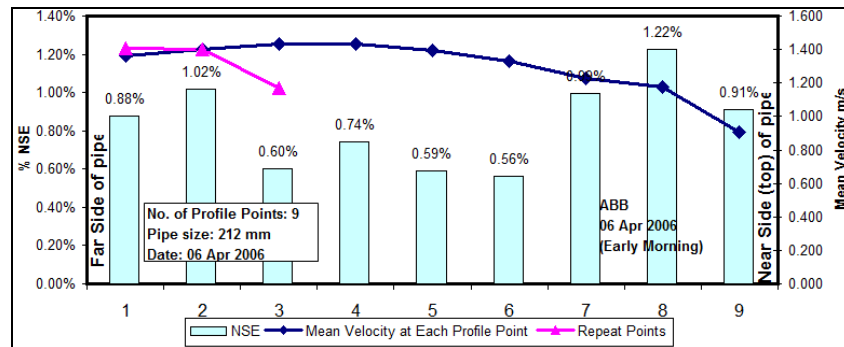


Figure 6.12: NSE plus mean velocity at each profile point

The 650B rig shows a similar skew, due to Fi correction, as at Hams Hall. However, the mean NSE is exactly half that at Hams Hall at 0.84%. There is less coherence in shape due to the less exact positioning of the probe achievable in the factory; $\pm 1 - 1.5\text{mm}$ compared with $\pm 0.1\text{mm}$ at Hams Hall. Maximum and minimum NSE excursions are a factor of 3.3 to 1.5 smaller, confirming the quieter hydraulics of the factory calibration test stand, relative to Hams Hall.

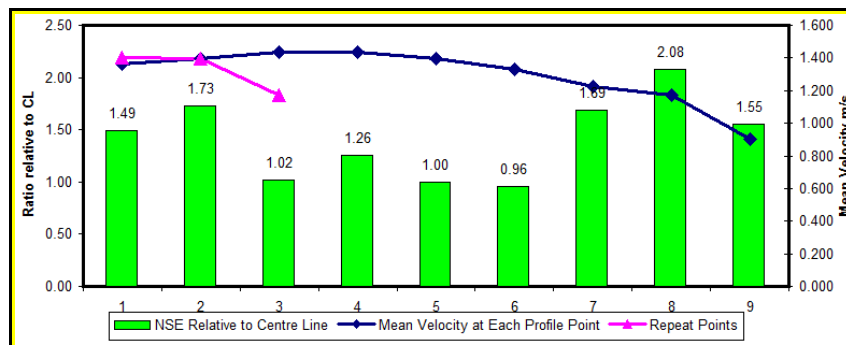


Figure 6.13: NSE relative to CL plus mean velocity at each profile point

When absolute values of NSE are normalised to the centre line, both the Hams Halls and 650B rigs generate similar statistics, with Hams Hall having a lower mean figure. This again reflects the smaller positional scatter. Both indicate fully turbulent developed conditions.

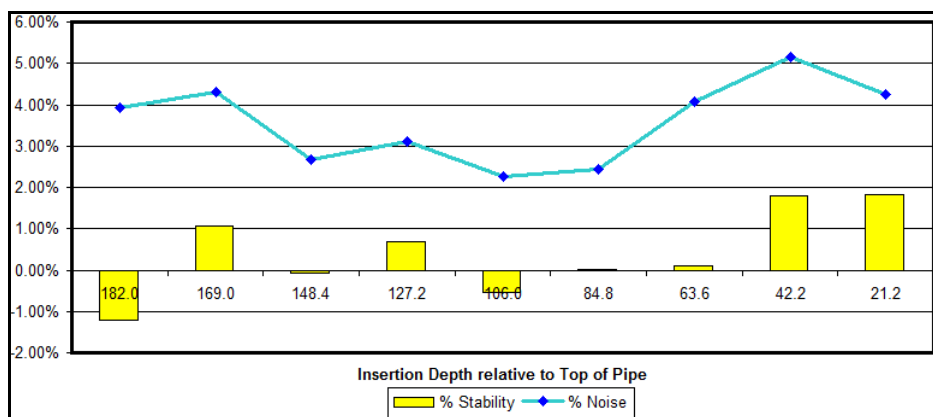


Figure 6.14: Noise plus % stability (plotted by insertion depth)

Noise, compared with the larger Hams Hall rig, is less than half with a mean of 3.58% and maximum excursions four times smaller.

Mean stability is comparable for both rigs at 0.41 and -0.43%; reference ABB's 650B line/Hams Hall 260 line respectively and reflects the pumped nature of both systems. However, active pump control of the 650B line is reflected in ABB's reduced maximum and minimum stability values which are 5 to 7 times smaller than at Hams Hall.

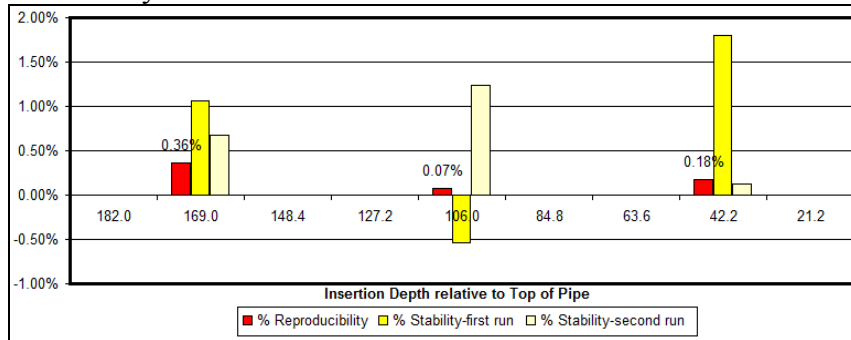


Figure 6.15: % Reproducibility plus stability (plotted by insertion depth)

Reproducibility values at ABB are similarly improved i.e. lower, compared with those at Hams Hall, reflecting the better control of bulk flow due to active pump control.

6.2.9 Summary of laboratory profiling performance

The foregoing experimental data concerning profile performance, reproducibility and repeatability demonstrates that, when using the developed software, the battery insertion probe can deliver good performance in relation to both velocity sensing and profile determination. It further illustrated that the general profile measurement method, as conducted using the same software, was robust and repeatable.

In detail:

- At Hams Hall the mean profile factor, F_p , derived from four separate trials conducted over four months at nominally the same flowrate, returned a value of 0.8491, +0.84%, -0.59%.
- Reproducibility was acceptable with the range of the three repeat points incorporated into each traverse, lying within an envelope of 0.13% to 2.17% i.e. close to 2 per cent.
- The best profile result achieved a span for the three repeat points of 0.09%.
- When a fifth, lower flow run is included, the mean experimental determination of velocity profile using the developed profiling software, incorporating multiple pipe disassemblies and rebuilds, is changed by 0.53% to $F_p=0.8446$.
- Variation of K , the factor related to the manufacturer's probe insertion factor F_i , is shown to significantly improve the appearance of the measured profile, but affects determination of the F_p , the profile factor, by 0.5% or less.
- Alteration of K does, however, strongly affect determination of the positions of the mean velocity positions within a profile. Consequently, use of either of the two mean velocity positions as an alternative to placing the insertion probe on the centre line is not advised.

- Optimum profile calculation requires values for the near wall Von Karman factor “m” and “K” to be input for every location. Where it is not possible to provide flow profile specific values for m and K the range of errors in calculated profile factor, F_p , will lie between -0.7% to +0.4%.
- Where a specific value for “m” can be set, the range of errors in F_i , with $K=0.5$ the manufacturer’s standard value and $K=1$, that value which optimised profile symmetry at Hams Hall, lies between +0.22% to -0.26%.
- NSE has been shown to be a useful description pertaining to the quality of profile signal quality and when ratio’d to the centre line value can provide information concerning the hydraulic symmetry.
- Practical knowledge of the quality of the profile factor, as generated by integration of the profile path velocities for verification purposes, can be significantly enhanced by examining individual path velocity statistics.
- The evidence from use of the profiling software on the manufacturer’s calibration line is that active pump control, combined with smaller pipework, achieves better hydraulic flow stability, a halving of NSE statistic and a general improvement in the other statistical descriptors.
- Degraded accuracy in the precision, $\pm 1.0 - 1.5\text{mm}$, achievable when locating the probe during traversing of the 212mm pipe on the manufacturer’s plant, lead to a deterioration in the characterisation of the profile, compared to Hams Hall.
- In absolute terms the profile factor, measured using the developed software equalled 0.827, differing from the textbook value of 0.850 used by ABB in calibrating probes by minus 2.7%. This contrasts with a difference at Hams Hall between results from the probe profiling software and the beam pitot of minus 0.6 %.

In summary, the Hams Hall reference line profile can be generated, regenerated and reliably determined over time using the developed profiling software to better than $\pm 1.0\%$ at a similar flow and better than ± 2 per cent when the flow range is extended.

6.3 PROBE FIELD PERFORMANCE, LIMITATIONS AND DATA QUALITY

Following investigation of the laboratory profile baseline performance the next step in advancing the primary objectives regarding improvement of data collection, data quality and knowledge of probe performance was to take the profiling methodology and software to site. Permission was negotiated to test the software at Severn Trent Water’s (STW) water production plant at Chaddesley Corbett in Worcestershire, the abstraction licence(s) for which are regulated by the EA. This site contains a series of boreholes supplying an elevated tank, which in turn feeds into the 300mm nominal bore distribution network under gravity. Hydraulically the probe tapping point is located approximately 20m (67diameters) downstream of a 90bend from the vertical reservoir outflow pipe; 14m (47diameters) downstream of the site WISPY electromagnetic meter with a 135degree bend, estimated to be 8m (27diameters) upstream between the meter and the tapping point. The location is one of the several hundred whose performance is verified by Severn Trent using a probe based technique and reported annually to the EA.

Excitation mode influence on probe performance

A key task of the initial site trials was to compare two models of EFM probe which were currently in use by STW. Both were from the same manufacturer and included the battery EFM probe design used for profiling at Hams Hall and at the manufacturer's plant.

The two EFM probe models were (a) the dc powered MagMaster model widely in use prior to the development of the battery technology and (b) the battery powered AquaMaster II probe. For the first design the transmitter associated with the probe sensor is effectively an ac powered device but supplied for field use with a dc to ac internal convertor so that operation is possible when supplied from a series of 12 volt car batteries.

The second unit utilises the transmitter tested in the Cranfield laboratory where it powered a full bore sensor and for field use is powered by internal lithium batteries. The primary difference between the two, according to the manufacturer's literature, was in the repetition rate of the field coils, with the battery EFM probe featuring a 15 second refresh period in contrast to the dc transmitter's nominal 1 second period.

Experience in the laboratory, prior to field testing, had indicated that the condition of the probe sensor tip could strongly influence calibration performance. In order to contrast the results obtained from the two excitation modes it was important to mitigate such influence factors. A strategy was therefore adopted which minimised the effects of both probe tip condition and electrode noise through the use of a single insertion assembly driven at different frequencies corresponding to those associated with the two models of EFM probe.

Because the dimensions of both dc and battery probe sensors are identically specified, potential differences which the use of two separate probes could bring about were thus circumvented. The results of operation in the two excitation modes are as seen in the following figures.

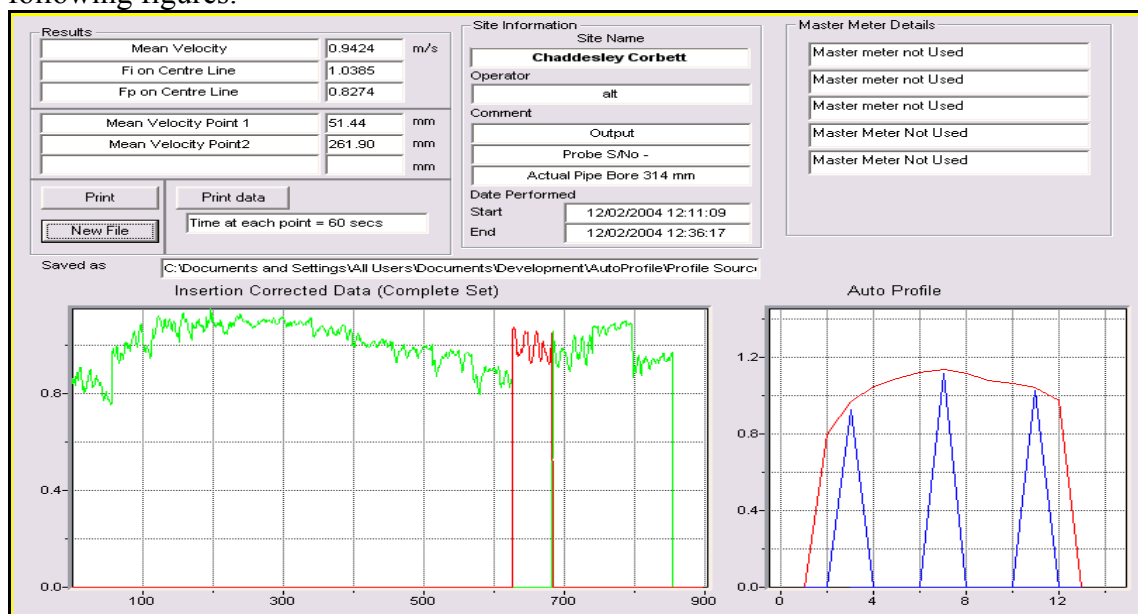


Figure 6.16: Chaddesley Corbett profile; dc probe excitation

Contrast the two profiles seen in figures 6.16 and 6.17:

- 1) the dc probe shows none of the discretisation seen in the velocity record of the battery equivalent powered probe;
- 2) the shape of the battery excited probe profile is badly distorted. Because of this no repeat points were attempted;
- 3) the calculated profile factors between the dc and battery excited probes are significantly different. For the dc probe $F_p = 0.8274$; for the battery probe equivalent $F_p = 0.9062$. A difference of +9.52% relative to the dc value.

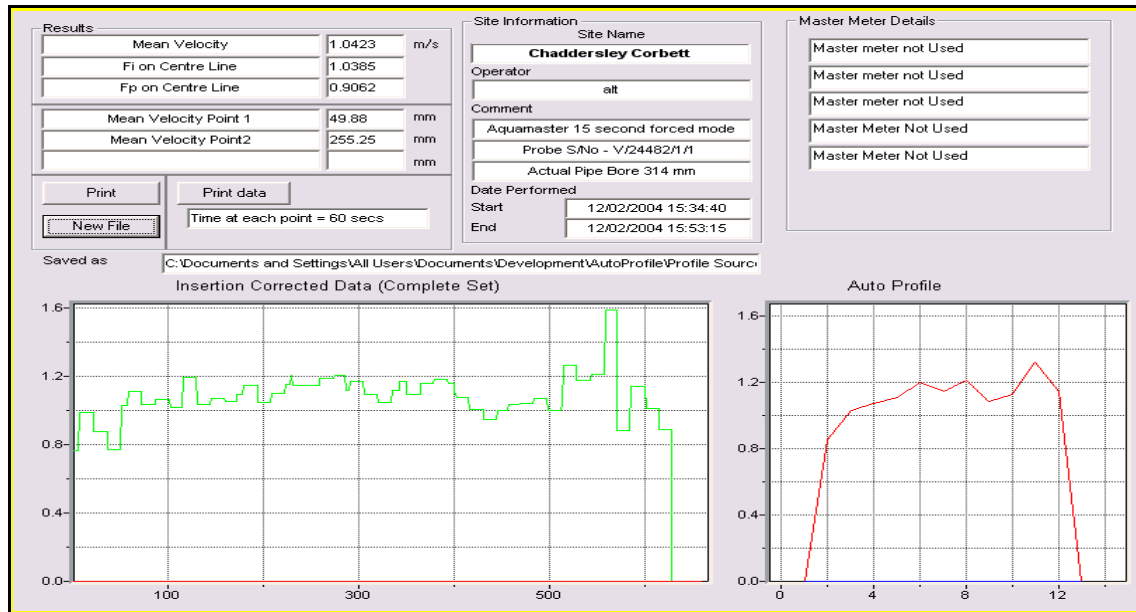


Figure 6.17: Chaddersley Corbett profile; simulated battery probe excitation

The differences are more easily seen when viewed on a shorter timebase, with the figure below showing the battery excited probe velocity readings in red and the dc excited probe results in blue.

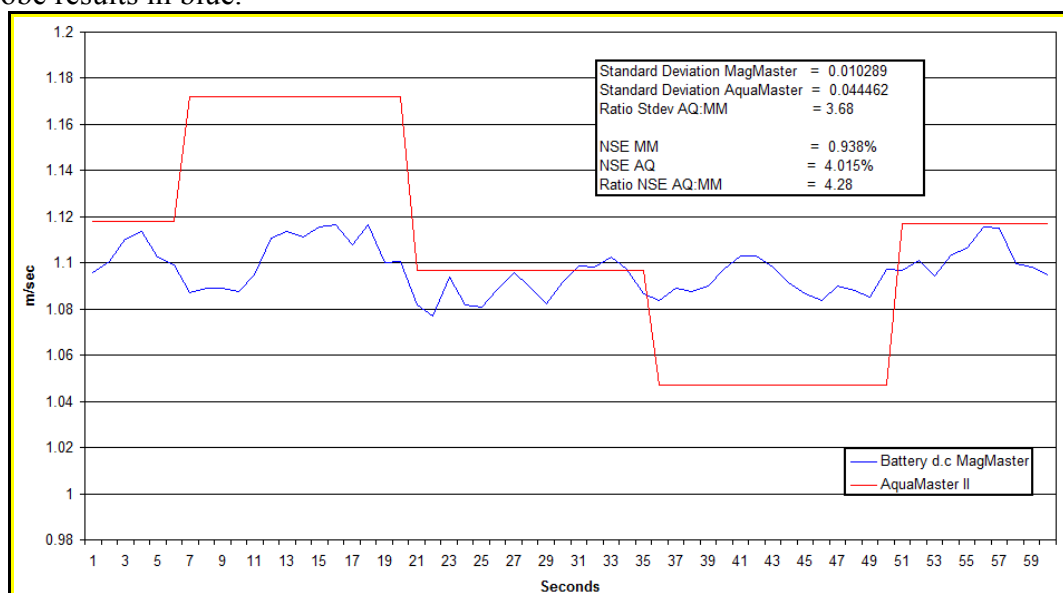


Figure 6.18: Excitation periodicity effects on centre line velocity

The conclusion drawn from the illustrated differences is that, in contrast to deployment as a surrogate full bore meter, the use of the battery EFM probe operating in its default, ex-factory, 15second, excitation mode is unsuitable for the measurement of representative point velocities when profiling.

This simple trial demonstrates the significant sensitivity of calculating a profile from data derived with a low frequency sampling regime, as employed by the battery EFM transmitter in its ex-factory state. Practically, use of the profiling software allowed the operator to graphically observe the build-up of the flawed profile, something which when using the standard “blind” profiling methods would not have been seen.

In respect of the quality of the data and the accuracy of the profile the trial casts significant doubt on the past quality of verification results which have submitted to the regulatory authorities using the ex-factory battery probe excitation settings.

6.3.1 Chaddesley Corbett field trial profile reproducibility

The ability to digitally measure and record individual point velocity values in real-time enables an illustration of the variability of the velocity signal to be graphically presented. Figure 6.19 shows this and one can observe that whilst the majority of paths are relatively stable over time, path P01, closest to the far wall of the pipe, shows drift in its value over the period of the sample measurement. This will be seen again in the later analysis graphs presented in the following section.

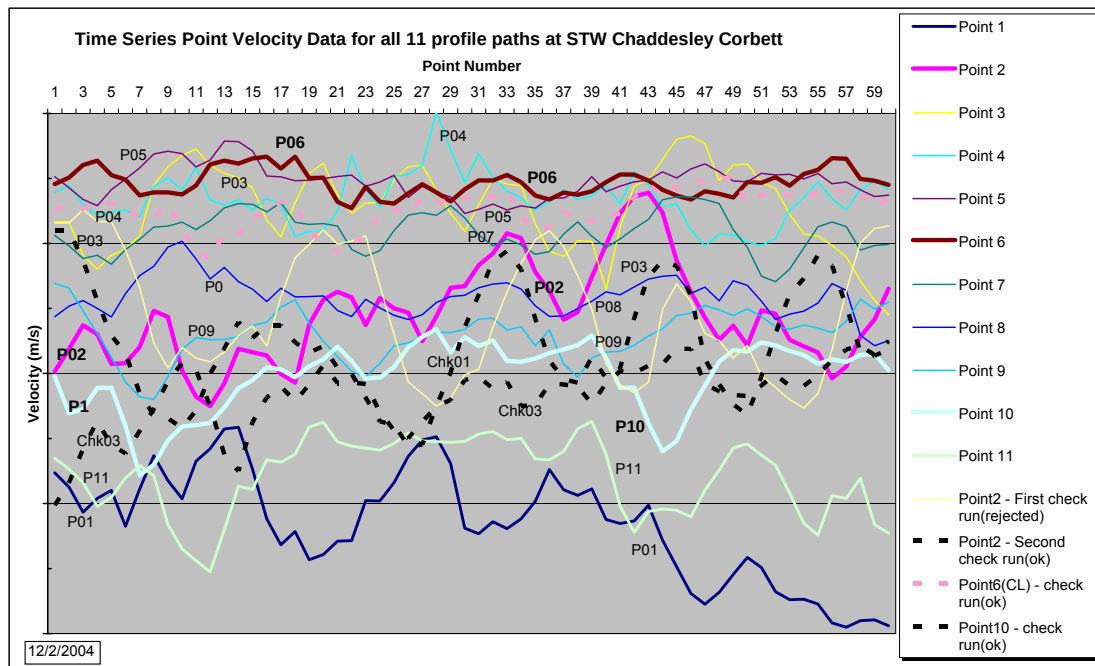


Figure 6.19: Chaddesley Corbett profile; individual real-time profile path velocities

Within this mass of data lie four runs which forms part of the quality check of all profiles measured using the developed software. One of these repeated runs, the first, for point P02 on the far side of the pipe failed the 5% inbuilt stability criterion, causing the operator to repeat the test.

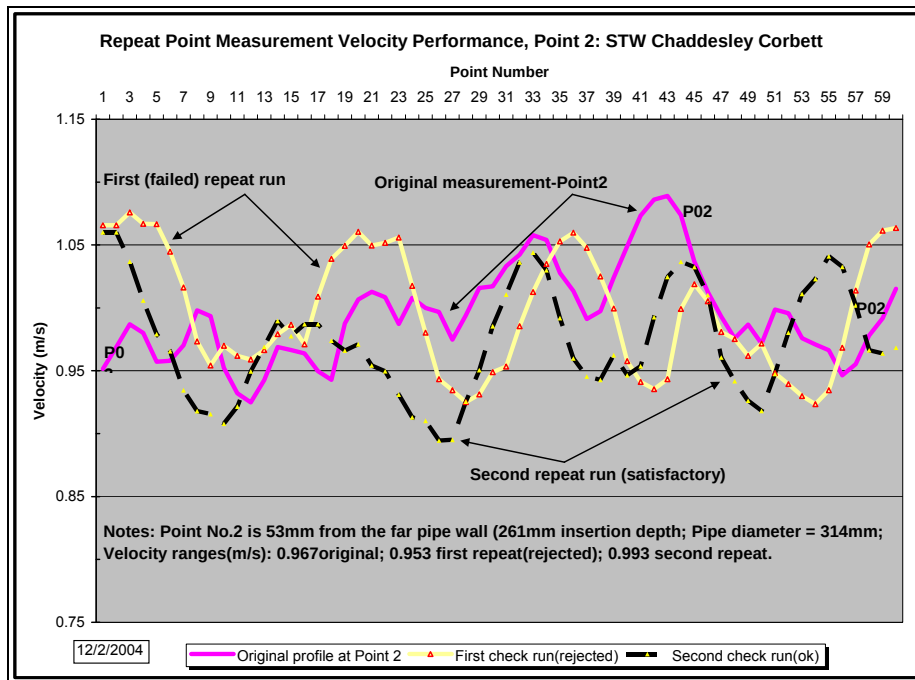


Figure 6.20: Chaddesley Corbett profile; repeat measurement detail, point P2

Figure 6.20 shows separately the P02 position results, illustrating the original velocity data obtained at that position plus the two repeat runs. As is evident, the changes in real-time velocities are such that, without the profiling software prompting the operator with the statistical analysis for noise and stability, use of visual evidence alone is inadvisable in deciding what constitutes acceptable data and which runs should be rejected or rejected. The summary of the three successful, repeat runs at Chaddesley Corbett is shown in table 6.4.

Profile Point No. (11 point traverse)	2	(Centre Line) 6	10
Av'. Path Velocity (m/s)	0.9687	1.1391	1.0454
Repeat Av'. Path Velocity post traverse	0.9532	1.1179	1.0295
Difference Reference Original Traverse	-1.6 %	-1.9 %	-1.5 %

Table 6.4: Chaddesley Corbett profile reproducibility

The conclusion from testing at Chaddesley Corbett was that under field conditions, on a non-pumped, gravity fed supply, it is possible using the developed profiling software to both achieve and to demonstrate reproducibility to a level of better than 2 %. Importantly, at -4%, the rejected repeat profile data result confirmed the importance to maintaining data quality of being able to observe the flow profile in real-time, so allowing the operator:

- (i) to make sense of the real-time data being logged and

- (ii) to be able to take informed action regarding acceptance or rejection of data, which will then go forward to form part of the formal verification performance report of that site.

When the preceding repeated profile figures are contrasted with those taken at Hams Hall (independent of the error sign), the Chaddesley Corbett results have a spread which is between 0.5% and 1.1% greater than in the laboratory, reflecting site conditions.

6.3.2 Graphed statistics for the Chaddesley Corbett profile

The complete list of profile statistics describing the probe performances at Chaddesley Corbett are set out in Appendix 13. However, whilst such a tabular list forms a useful record for site to site and test to test comparisons, graphical representation of the individual measured velocities provides a better means to illustrate local hydraulic phenomena which may impact data quality.

Four graphs are presented which list the standard statistics for the measured path velocities, namely: (i) normalised standard error (NSE); (ii) NSE normalised to the centre line value; (iii) noise; (iv) stability and, (vi) variable expanded uncertainty. The last statistic aims to illustrate the spread of apparent variation in data quality which may be introduced by the operator if the time constant of the probe transmitter is altered.

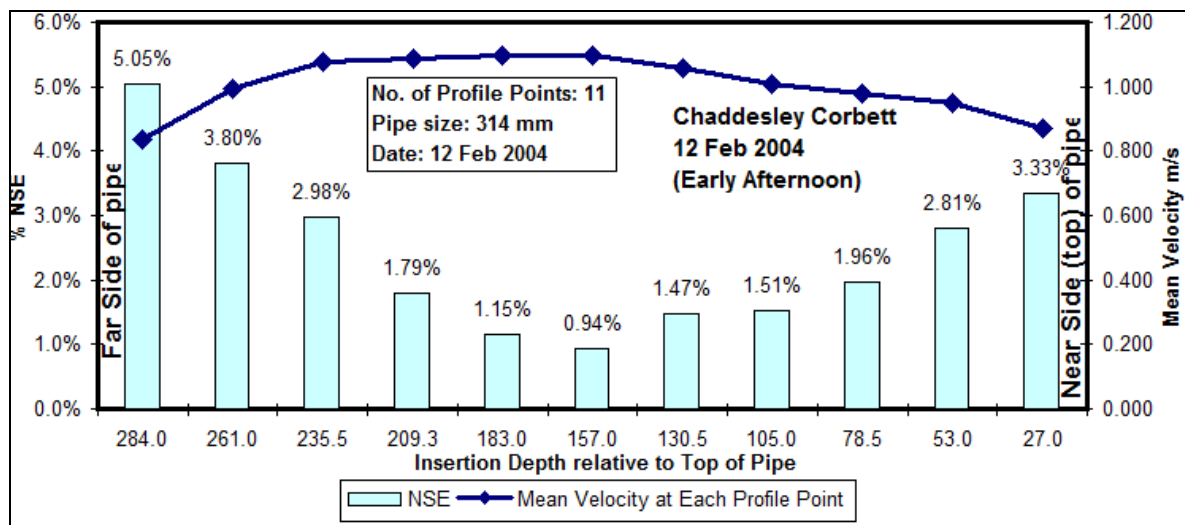


Figure 6.21: NSE plus mean velocity at each profile point

The asymmetry of the NSE values is seen to be associated with closeness to the far wall.

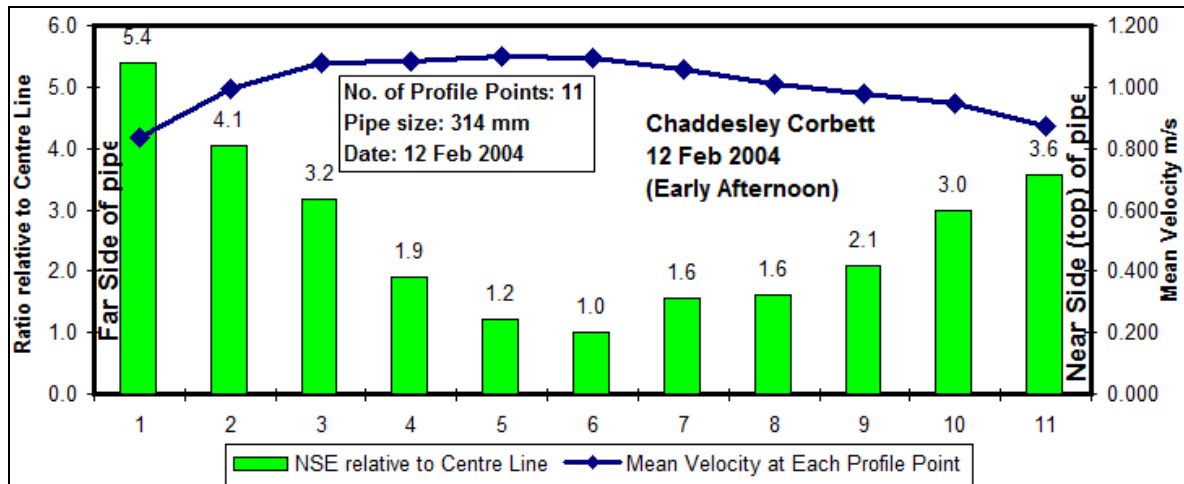


Figure 6.22: NSE relative to centre line (plus mean velocity at each profile point)

When referenced to centre line, the value is 50% higher than the Hams Hall average.

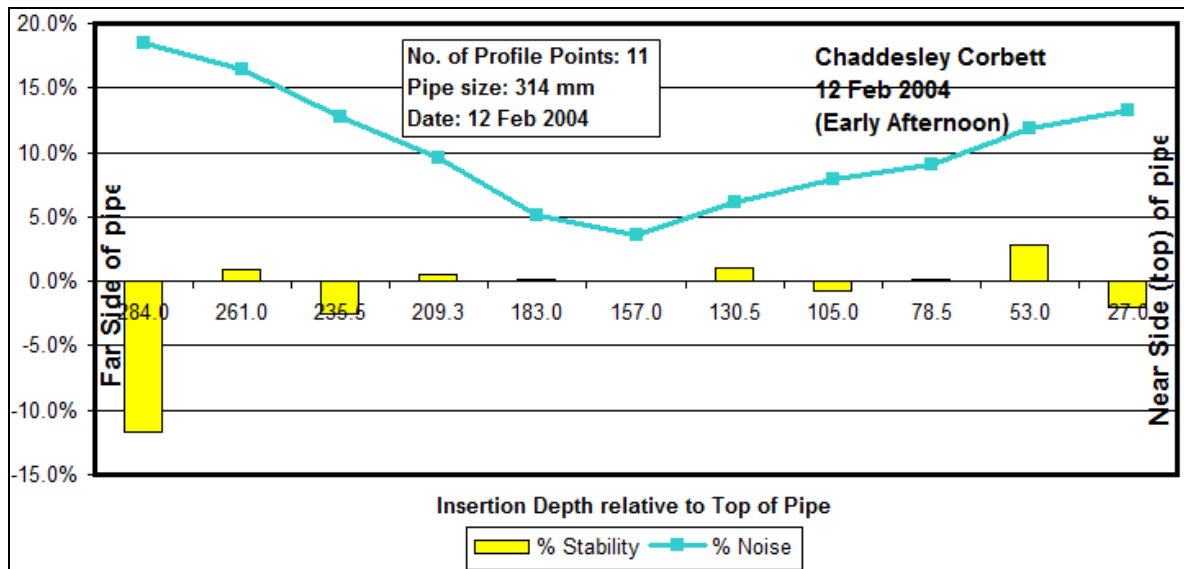


Figure 6.23: Noise plus % stability (plotted by insertion depth)

Whilst stability is on a similar level with laboratory performance, the mean Noise statistic is 38% greater, reflecting local hydraulic conditions. However, the last profile point on the far side of the pipe can be seen to be significantly less stable, indicating either a change in the short term flow into supply or the possible influence of vibration on the probe.

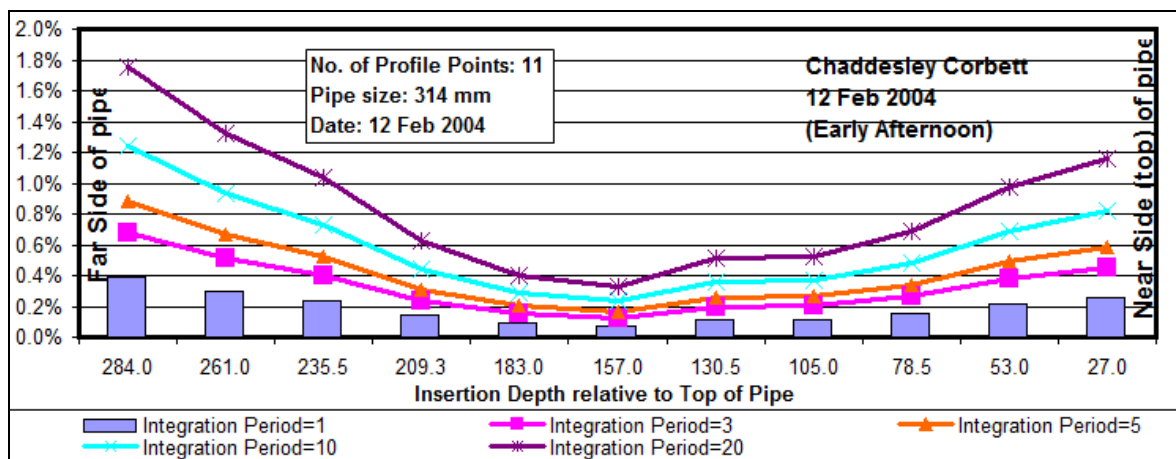


Figure 6.24: Variable expanded uncertainty (plotted by insertion depth)

The data, whilst not as good as that in the laboratory, exhibits a spread of values which, depending upon the chosen method of calculation can overlap with the laboratory figures. This illustrates that an injudicious choice of integration period programmed into the probe transmitter can have the effect of obscuring real differences in short term data quality.

6.3.3 Additional field profiling results

Following the work at Chaddesley Corbett a series of tests were conducted at other STW sites [82]. The focus of these tests was mainly to resolve past queries which had arisen with the year to year verification results obtained with standard profiling practice [62]. One site, Tower Wood, had been the subject of widely varying results from annual verification to annual verification. It therefore offered the opportunity to better establish the performance limits of site based battery probe profiling reproducibility achievable when using the developed software.

Tower Wood profile repeatability and reproducibility

The trials on the 300mm nominal bore Tower Wood meter were conducted over two days to assess the level of site profile repeatability and reproducibility. The site consists of a single outflow meter approximately 20m (65diameters) downstream of the borehole headworks. The flow is pumped and supplied by a submerged multi-stage borehole design. Previous to this only manual repeat profiles had been possible and had created wide variations, greater than 8%, in the verification results leading to uncertainty regarding the accuracy of the installed WISPY station meter. The extent to which the developed profiling/verification package could demonstrate improvements in the assessment of the location was therefore the primary aim.

Tuesday04October05, PM.

The profile is show below. It was taken in early afternoon at the end of the lunchtime period, catching the change in flow pattern which typically occurs then.

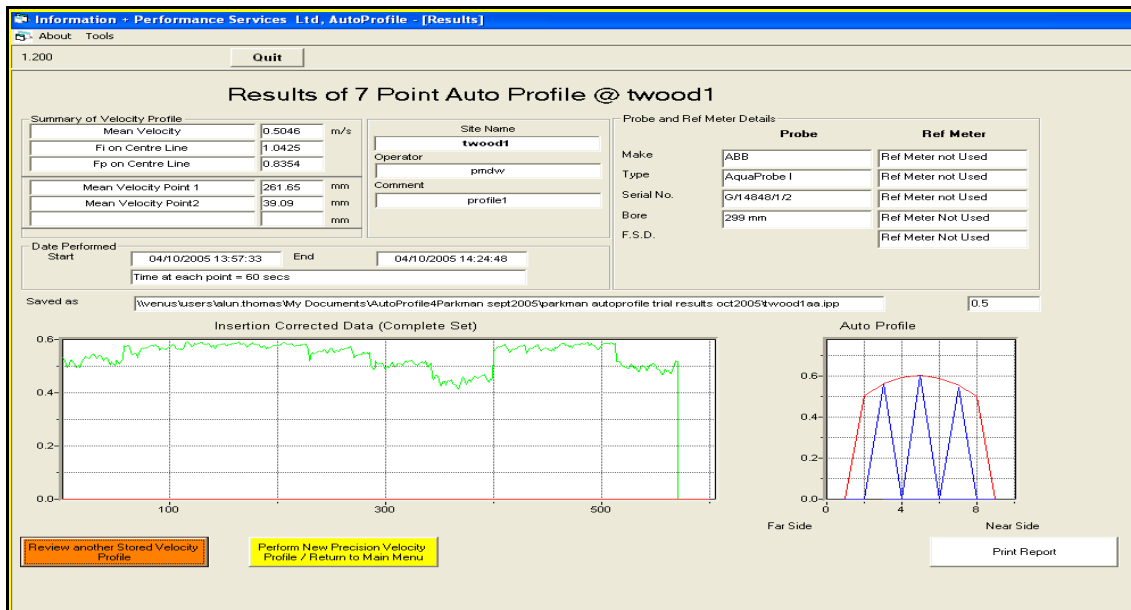


Figure 6.25: Tower Wood Tues04Oct05 profile - 13:57 to 14:24

Historically, the site profile performance had been observed to change significantly between annual verifications. Deploying the developed software aimed to objectively examine the extent to which previous changes could be attributed to either true differences in the site hydraulics or to operator/equipment derived errors.

Wednesday05October05 AM

A repeat profile taken the next day between is shown below:

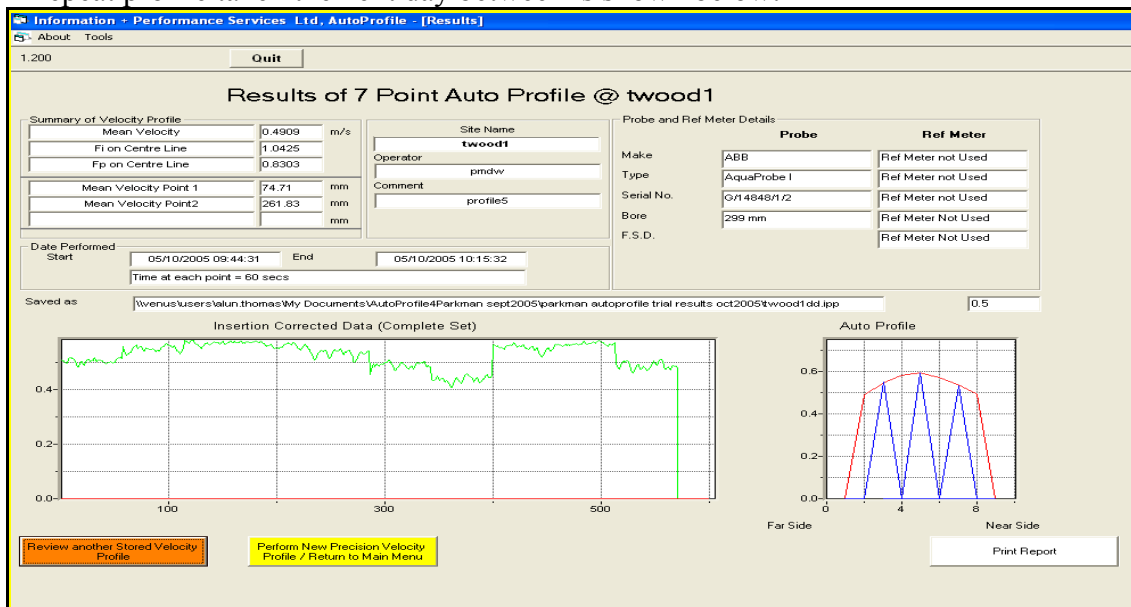


Figure 6.26: Tower Wood 05Oct05 profile – 09:44 to 10:15

Wednesday05October05 AM

A second profile was taken later the same day:

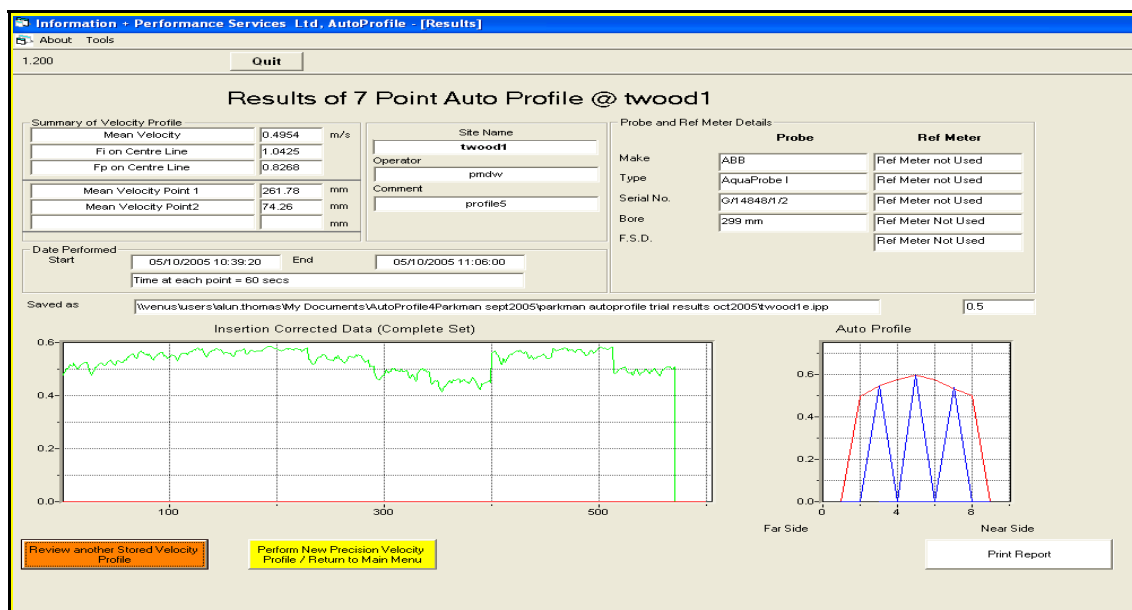


Figure 6.27: Tower Wood 05Oct05 profile – 10:39 to 11:06

Figures 6.28, 6.29, 6.30 and 6.31 illustrate a set of statistics for the data from the Tower Wood site. Figures 6.28 and 6.29 show the individual path velocity normalised standard error, (NSE) plus the same NSE values normalised to the centre line figure. Figures 6.30 and 6.31 describe the noise, stability and variable expanded uncertainty statistics.

The summarised result for the three profiles is given below in figure 6.28 below.

KEY: 1aa - data from pm of Tuesday04October05
1dd - data from am of Wed05October05
1ee – data from pm of Wed05October05

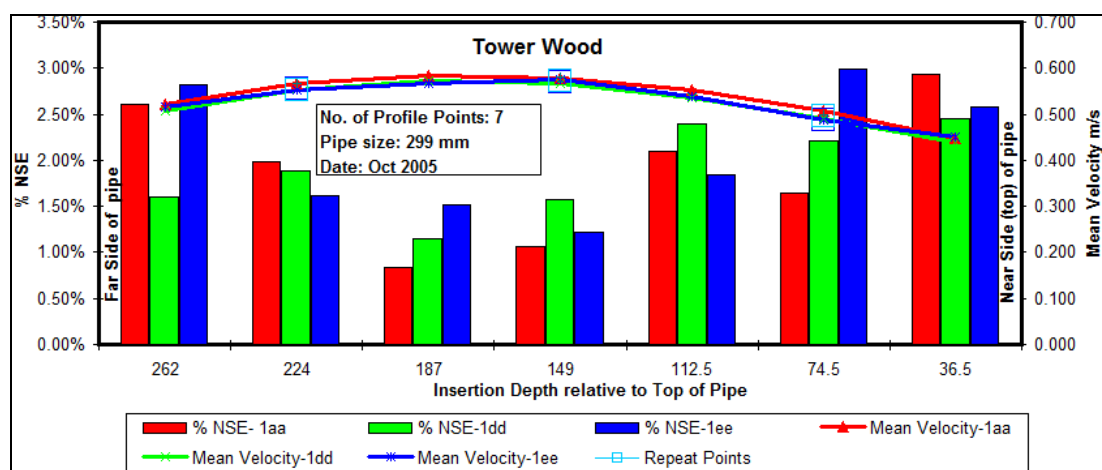


Figure 6.28: % NSE for Tower Wood (plotted by insertion depth) with mean velocity

As can be seen, the values of NSE spread from a maximum of close to 3% to below 1%. These are on a par with the laboratory mean data and illustrate good on-site profiling performance.

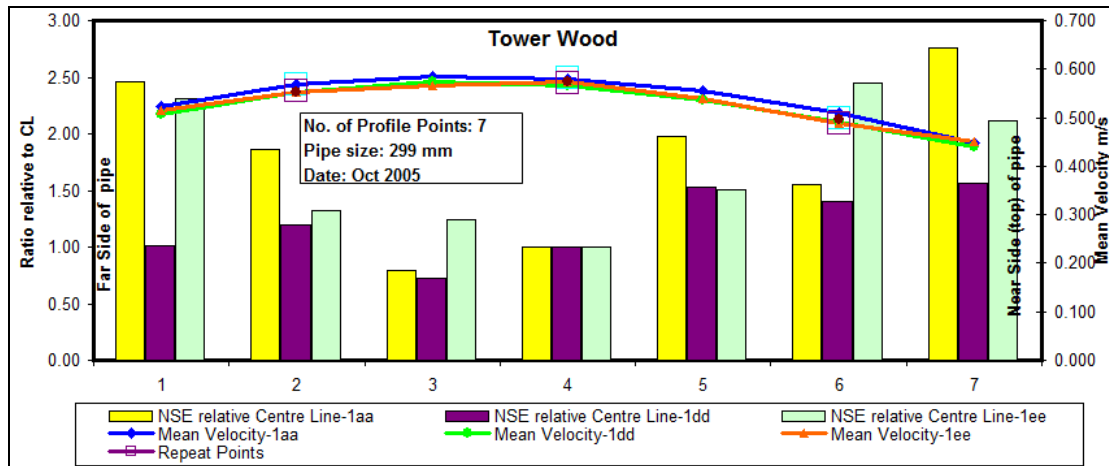


Figure 6.29: NSE relative to centre line: incl mean velocity at each profile point)

The normalised NSE plot show that the profile quality falls away close to the pipe crown. Nevertheless, the span of values is smaller than the laboratory average for the Hams Hall 260mm pipe, although the value of Re , at 146 000, is less than half that in the laboratory.

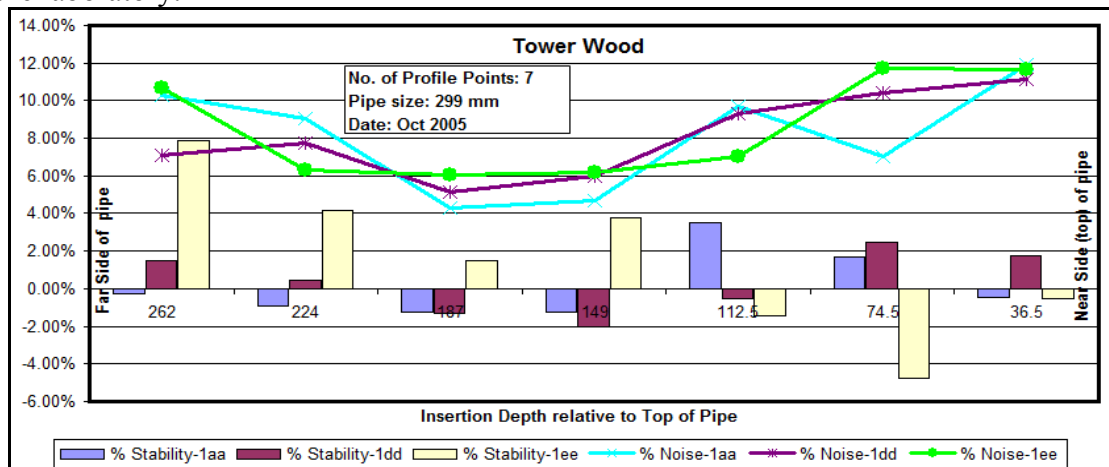


Figure 6.30: Noise plus % stability (plotted by insertion depth)

In terms of Noise and Stability the profiles at Tower Wood appear to be very good.

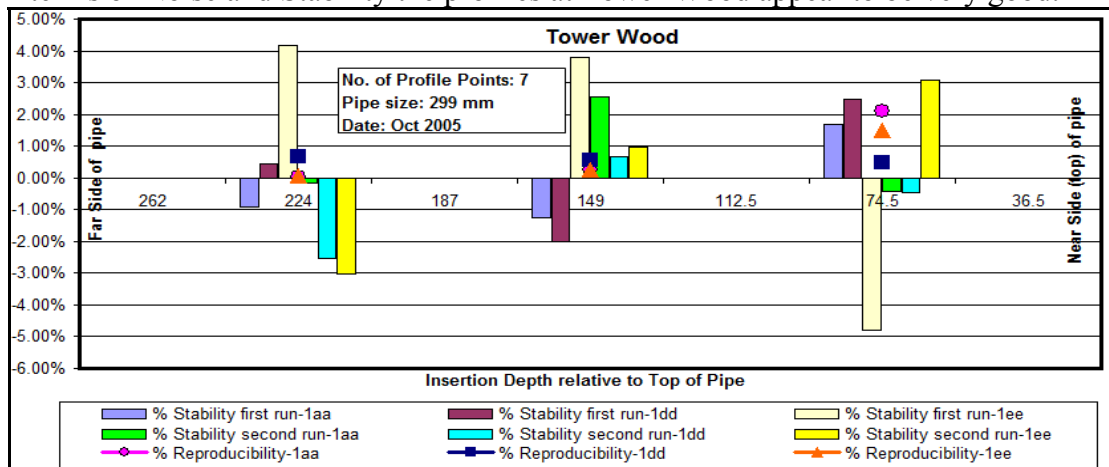


Figure 6.31: Reproducibility plus stability % for Tower Wood (plotted by insertion depth)

However, data from the third run indicates that there had been changes in the bulk flow which affected the statistics. This is a particular case where, if normalisation of the measured profile velocity points against the station meter had been implemented, the data quality could have been improved. Generally, for this site the stability statistic spanned $\pm 3\%$ to $\pm 4\%$ which, although acceptable, could be improved by the use of normalisation.

Tower Wood site review

The summary of all three profiles is as follows:

Meter Location & Designation	Tower Wood Test1	Tower Wood Test2	Tower Wood Test3	Mean Repeat values	Standard Deviation Rpts
Date	04/10/2005	05/10/2005	05/10/2005		
Time	13:57:33	09:44:31	10:39:20		
	14:24:48	10:15:32	11:06:00		
D (mm)	299	299	299		
Mean Velocity (m/s)	0.5046	0.4909	0.4954	0.4970	0.70%
No. profile points	7	7	7		
Fi	1.0425	1.0425	1.0425		
Fp	0.8354	0.8303	0.8268	0.8308	0.43%
Vm posn1	261.65	74.71	261.78		
Vm posn2	39.09	261.83	74.26		

Table 6.5: Tower Wood summary profile data

The averaged value for Fp is thus 0.8308, with the maximum and minimum taken over the two days and three test runs at $+0.55\%$, -0.49% .

Table 6.6 shows the exact day to day changes as follows:

	Relative Velocity change	Relative Profile changes
Day2 to Day 1 change (relative to Day1)	-2.72%	-0.61%
Day2 run no.1 to Day2 run no.2 change (relative to Day2 run no.1)	0.92%	-0.42%
Day2 run no.2 to Day1 run no.1 change (relative to Day1 run no.1)	-1.82%	-1.03%

Table 6.6: Tower Wood - relative day to day velocity and profile changes

Each of these individual results is close to that achieved in the laboratory environment.

Velocity Profile value relative to the mean Fp of all the site trials	Day1 run no.1	Day2run no.1	Day2 run no.2
Percentage difference	0.55%	-0.06%	-0.49%

Table 6.7: Tower Wood – profile repeatability summary

Table 6.7 illustrates the spread for the measured velocity profiles, relative to the three test mean, falls just outside $\pm 0.5\%$. This is a very good result which has not previously been reported as having been achieved in an operational environment.

On the basis of the evidence produced using the developed profiling software it can be concluded, within reason that the differences seen in previous years at this site are attributable to operator and equipment related issues and are not a function of the pumped flow hydraulic characteristics of the site.

6.3.4 Summary of the field trial findings

To deliver satisfactory profiling performance on-site it is essential that the excitation rate of the battery probe is reset from that programmed, ex factory, by the manufacturer. Failure to do so will lead to gross errors when profiling.

The use of an interactive profiling methodology, whereby the operator is exposed to the quality, statistics and shape of the developing profile proved to be very helpful. Visualisation, in real time, of the measured point velocities fundamentally changes the operator's ability to control the situation and hence to delivery qualified, quality, profile results.

In particular, the choice available as to whether to accept or reject data demonstrated that data quality can be measurably improved by circumventing limitations imposed by flowrate events which can distort the usual profiling/verification process.

Repeatability of a particular profile must be demonstrated if an operator is to legitimately characterise the uncertainty of a meter verification using the battery probe methodology.

The saving of all measurements, equipment details, times and key statistics in a form which can be recalled and analysed allows the operator to traceably demonstrate profiling performance both qualitatively and quantitatively.

The statistics generated at Chaddesley Corbett show that whilst noisier and marginally less stable relative to the laboratory, this particular location delivered data of acceptable quality and with a profile reproducibility better than 2%.

From the tests at Tower Wood the achievable limits for profile repeatability and reproducibility using the battery probe methodology were shown to be in the range close to $\pm 0.5\%$. This is a result which, without the use of the developed software would have previously been very difficult to demonstrate.

The discrepancies in year to year profile values reported at Tower Wood were able to be resolved using the developed software methodology, being shown to be equipment and operator dependent, rather than hydraulically sourced.

Use of the NSE, noise, stability, reproducibility and variable expanded uncertainty set of statistics successfully provide quantifiable indicators which can be used to assess the quality of a site's verification performance.

Absolute errors can still exist despite the measurement of stable and repeatable profiles. The identification of such hydraulics should prompt the site management to augment the usual verification based on a single, vertical profile traverse with one employing a

second, orthogonal traverse as per NEL guidelines. However, this is not always possible.

The levels measured for NSE, noise, stability, etc overlap the baseline laboratory data and show that uncertainty limits may be subject to variability introduced by operator programming of the probe transmitter.

Where flows vary during the test period, profiling performance could be further improved by normalisation of the profile runs with respect to the bulk site station meter flow, provided that a signal feed can be made available

Process driven design of the field profiling software has enabled delivery of consistent results irrespective of individual operator. It is fundamental to establishing a consistent verification methodology which can be administered by regulators.

6.4 RE-EXAMINATION OF PROBE VIBRATION LIMITS

During the site work it had been observed that the stability and NSE statistics showed elevated values for points close to the far wall of the pipe for larger pipe sizes, 450 and 600mm. As with the value of “K” the only published guidance relating to the limitations of the probe technique when deployed in larger pipes or at higher velocities was manufacturer derived. Therefore, in line with the stated strategy of examining both the performance and limits of the battery probe verification technique, a re-examination of the limits for which flow induced vibration was likely to impair the insertion probe measurement was undertaken.

6.4.1 History of mechanical design of probe

The present insertion probe design, shown previously in figure 3.7 and 3.8, has its origins in a unit originally developed by the Water Research Centre, WRc, in the middle 1980's. After acquiring this design a process of standardisation was undertaken by the present manufacturer, ABB. This offered the possibility of generating a uniform approach to assessing the sensitivity to vibration for the battery probe, because all key components, comprising (i) the probe stem inserted into the pipe, (ii) the top connection box and, (iii) the support sleeving and locking assembly are the same for different models. Hence both hydraulically and modally a set of standard conditions could be modelled.

6.4.2 Basis for calculating probe fundamental vibration and associated velocity limits

The determination of the limits for frequency and velocity require that the effects of vibration are assessed in respect of:

- (a) the part of the probe which is inserted into the pipe and
- (b) that part which remains outside the pipe above the tapping/gate valve assembly.

Both modes are able to critically influence the ability of the probe to accurately measure velocity. Both therefore require to be incorporated into determining the limits within which a probe of a known length can be safely and accurately operated.

Utilisation of empirical equation set

No information relating to the particular probe vibration frequency was found in the open literature. However, confidential work by R Turner, undertaken over 25 years ago, was made available [83, 84]. This empirical work closely matches the dimensions of the present battery probe and forms the basis of the spreadsheet calculations undertaken. For a probe partly inserted into a pipe filled with water, Turner derived the following expression for the fundamental internal frequency of vibration:

$$F_{REQ} \text{ (internal)} = 18,947,557 * (L_{INS-UN})^{-2.0257} \quad (6-7)$$

and for the corresponding condition related to that part of the probe outside of the pipe:

$$F_{REQ} \text{ (external)} = 6195.06 * (L_{EXT})^{0.989129} \quad (6-8)$$

where the critical lengths L_{INS-UN} and L_{EXT} represent the unsupported probe length either inside or outside of the pipe.

Given these two equations a spreadsheet can be constructed to calculate $F_{REQ} \text{ (internal)}$ and $F_{REQ} \text{ (external)}$. Nevertheless, it must be clearly noted that it remains an empirical approach.

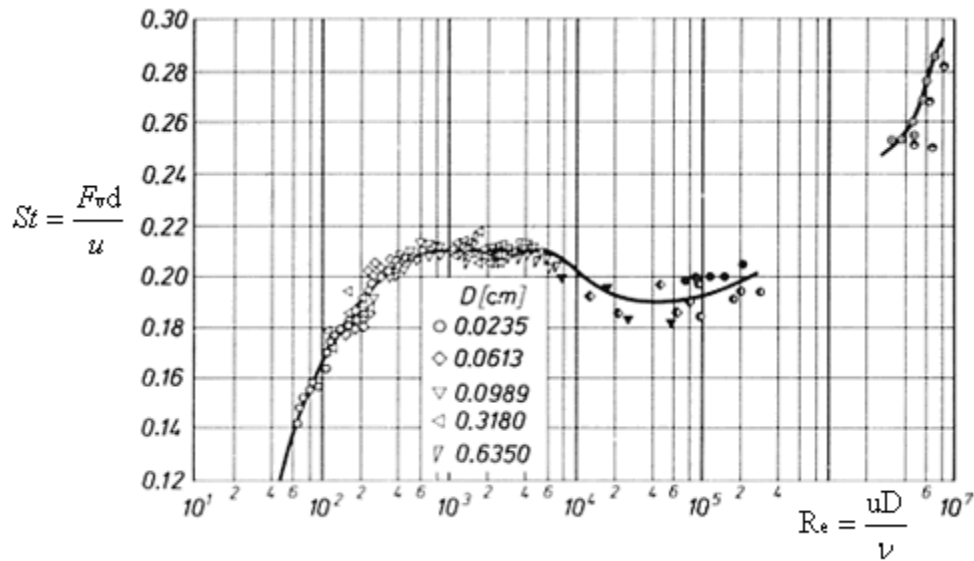


Figure 6.32: Strouhal number as a function of the Reynolds number

As is shown in figure 6.32, the relationship between St and Re varies considerably. Strouhal number St [85], is a function of Reynolds number, Re and is proportional to the reciprocal of vortex spacing, expressed as a number of obstacle diameters. For the particular calculations undertaken St was approximated and set to 0.2. The second underlying approximation is that the critical shedding point is coincidental with the calculated frequency, as given by:

$$F_{critical} = \frac{St \cdot \nu}{d} \quad (6-9)$$

Where St = Strouhal Number; v = fluid velocity; d = the diameter of the probe, more exactly termed the characteristic length.

This defines the fundamental relationship between critical frequency and velocity. Therefore, in conjunction with figure 6.33 consider the approximations which are inherent both in the process and in the calculations, some of which relate to the application of the Strouhal equation.

Figure 6.33 shows the general plan of calculation followed, with the modelling approach built on the empirical information supplied by Turner set out below.

The determination of the frequency limit starts with Turner's frequency formula for the section of the probe internal to the pipe.

The spreadsheet then back calculates the equivalent velocity using the Strouhal number relationship.

Once this velocity is known, a value can be generated for the drag on the probe under that condition.

Finally a value for the approximate probe deflection is determined, simply by equating the probe to a spar and calculating the deflection due to the drag force.

The spreadsheet input variables are thus all physical descriptors for the probe size, material, shape and length, including the inner and outer diameters of the tubing from which the probe is constructed. In addition, one requires physical details of the point of support for the probe, which in turn sets three lengths: (i) the unsupported probe length; (ii) the length of the probe gland; and (iii) the length of the tapping, all of which are input variables.

Importantly, in recognition of the approximate nature of the calculation, the outputs are assigned within a confidence band, achieved by scaling the raw calculations. This confidence band sets high and low limits on the frequency and velocity boundaries. For the calculation undertaken the tolerances have been assigned on the basis of experience, including laboratory testing, and are open to challenge. However, at present and in the absence of additional measurement they represent reasonable engineering tolerances.

For the calculations shown the confidence band was set using high and low limits achieved by the use of multipliers set to 1.3 and 0.6, respectively. A sample calculation from the spreadsheet is shown in Appendix 14, the columns showing the stepwise calculation of limit velocity through to probe deflection.

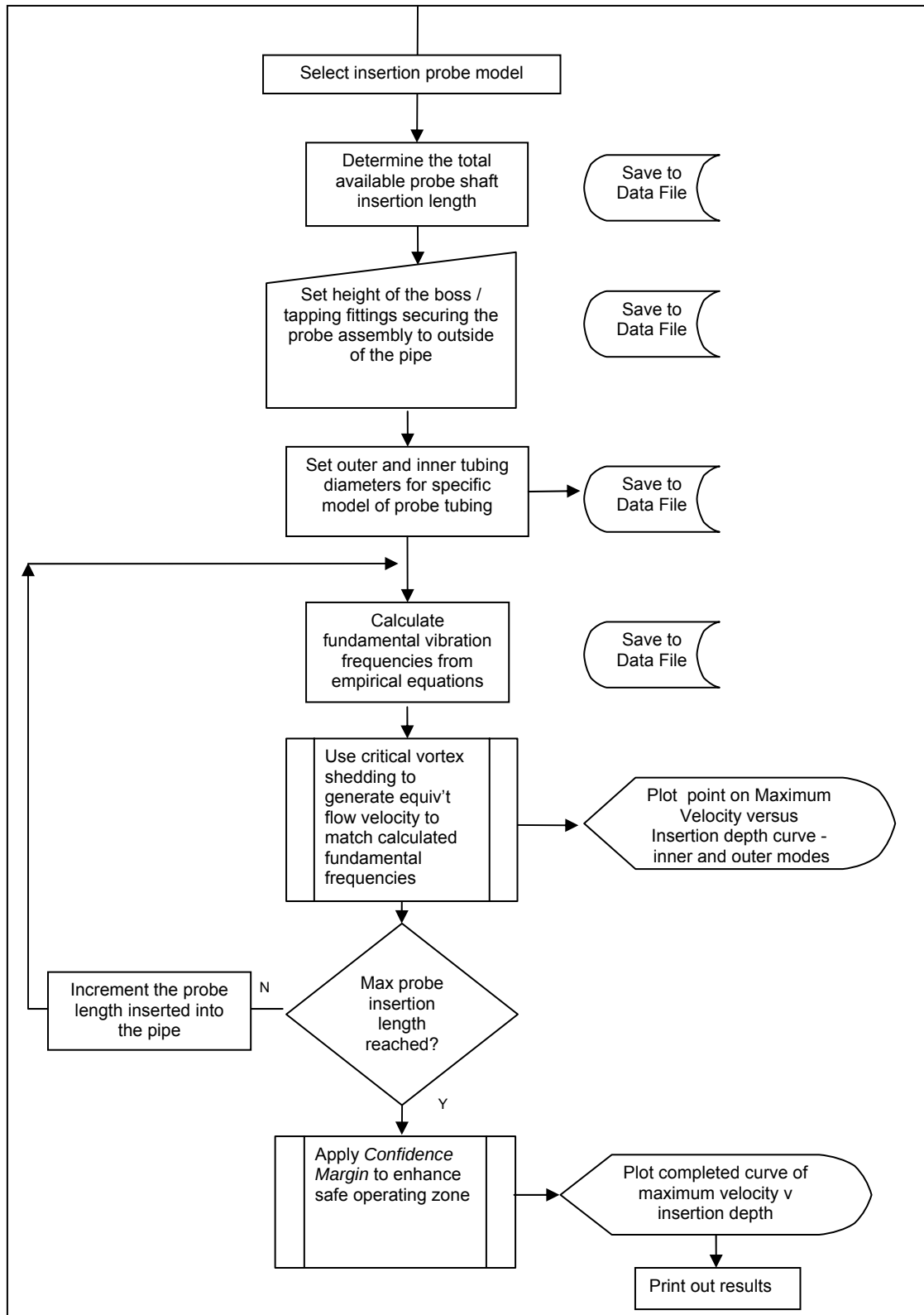


Figure 6.33: Flow diagram for determination of probe critical vibration limits

6.4.3 Probe frequency and velocity limits

Figures 6.34 to 6.37 show the plots of probe frequency against insertion depth, first for a 300mm probe and then for a 2000mm design. These lengths were chosen because they represent the largest and smallest standard production probes having the same diameter.

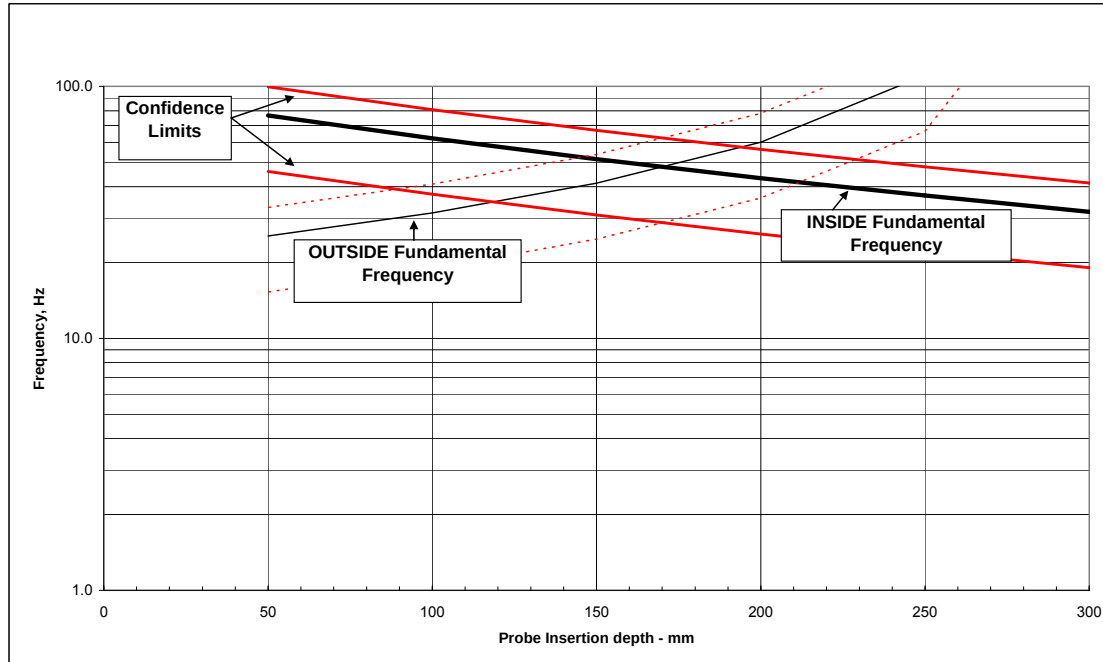


Figure 6.34: Vibration frequency limit curves – 300mm length probe

For the smaller probe, the frequency is always above 30Hz, even at maximum insertion depth. Applying confidence limits lowers this to around 20Hz.

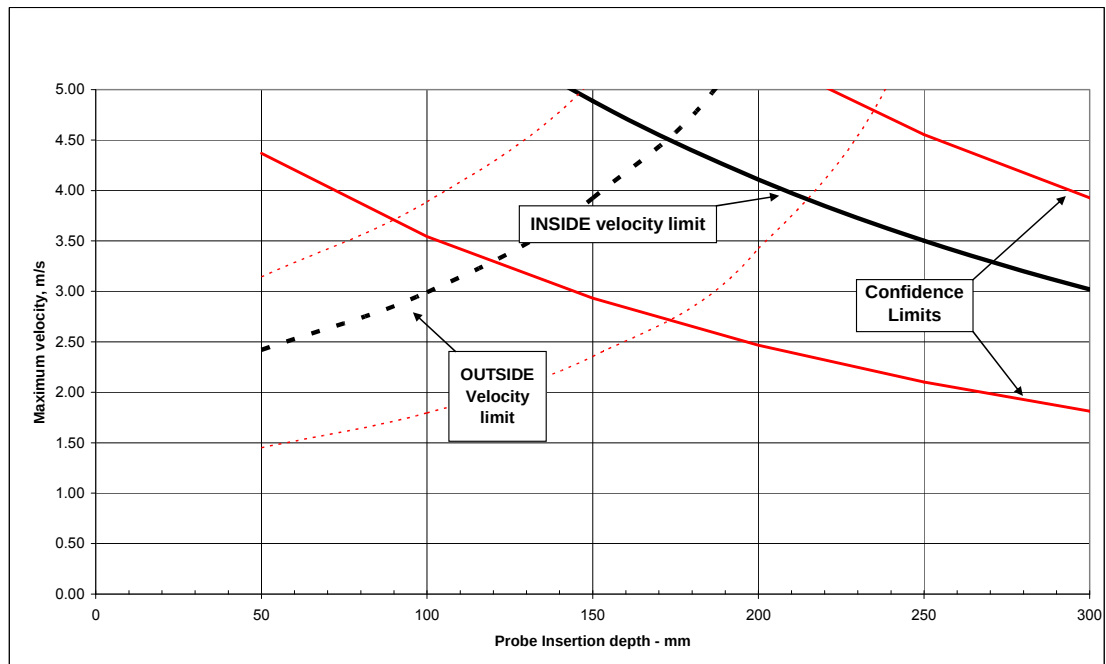


Figure 6.35: Velocity limit curves – 300mm length probe

Figure 6.35 translates the fundamental frequency, generated from the empirical frequency formula, into a limit velocity by equating it with the critical vortex shedding frequency. For the 300mm probe this indicates a safe working boundary velocity of approximate 3m/sec velocity when fully inserted. Once confidence limits are applied this figure reduces to under 2.0 m/sec. This is approaching velocities which are representative of the flows found in many water network supply systems.

Figure 6.36 illustrates the equivalent frequency limit curve for a 2000mm probe.

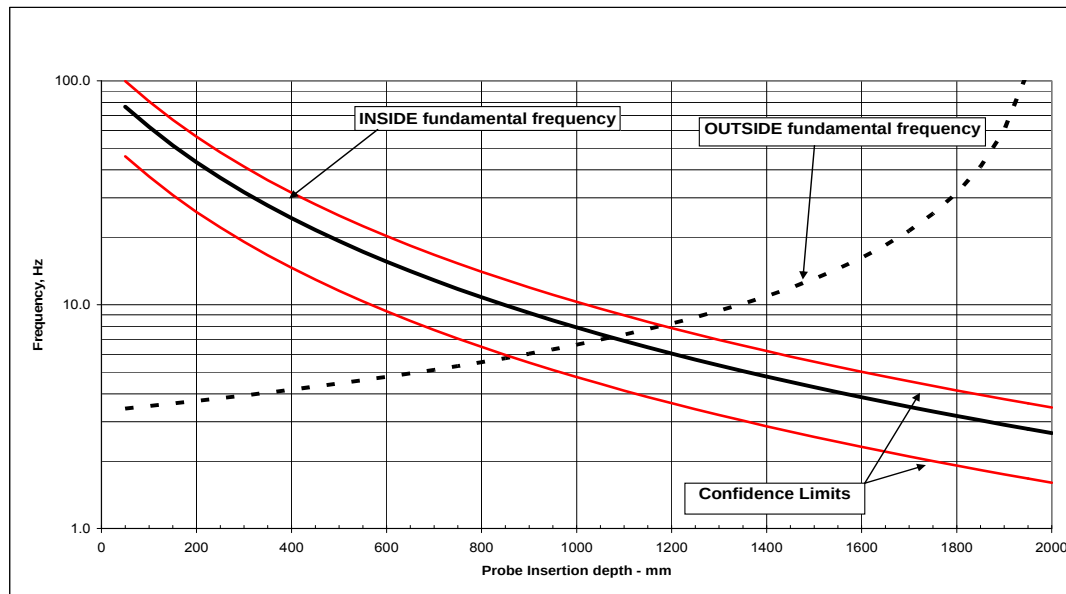


Figure 6.36: Vibration frequency limit curves - 2000mm length probe

The 2000mm probe result differs significantly from that of the 300mm unit with the fundamental frequency spanning 6Hz at 1200mm insertion. When the confidence band is applied this is lowered to around 3.6Hz.

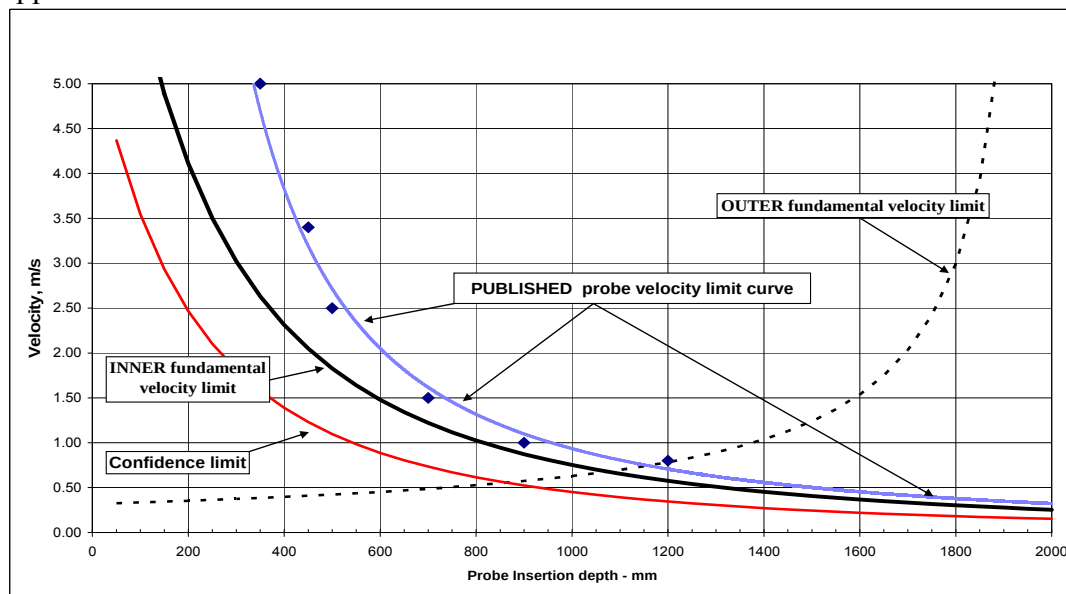


Figure 6.37: Velocity limit curves – 2000mm length probe

Figure 6.37 translates the 2000mm probe fundamental frequency into a limit velocity. The same figure also shows the limit curve published by the manufacturer from which it is apparent that the published values differs significantly from that recalculated using the spreadsheet. Stated another way, when used for profiling/verification purposes the calculated velocity limit is approaching a value where it could become a critical factor in the universal use of the insertion probe.

Table 6.8 contrasts the values presently calculated with those published. What can be observed is that in the 400mm to 600mm insertion length range is that the revised, non manufacturer calculated, limits indicate that with vibration limits below 2.31 m/sec and 1.48 m/sec respectively, there exists a reasonable likelihood that the probe will meet these limits when operating under representative network flow regimes.

2000mm Long Insertion Probe	Manufacturer Probe Velocity Limit (m/s)	Thesis Calculated Probe Velocity Limit (m/s)	Limit after Confidence factor applied (m/s)
400mm pipe	3.80	2.31	1.39
600mm pipe	2.05	1.48	0.89
1200mm pipe	0.80	0.57	0.34

Table 6.8: Comparison of manufacturer and thesis calculated probe velocity limits

Applying the confidence band lowers the limits for the 400mm to 600mm length probes to 1.9m/sec and 0.9 m/sec respectively. These are velocity values which are known to lie in the normal operating flowrate regime of 400mm to 600mm supply pipes. At 1200mm the limit is 0.57 m/sec, or with the confidence factor applied, 0.34 m/sec.

All the recalculated values lie significantly below ABB's published recommended limits. This has important practical implications for profiling / verification purposes and potentially represents a significant limitation to the general applicability of the probe technique for meter verification.

6.4.4 Effect of tapping length on lowering probe velocity limits

As common sense would suggest, the effective probe length which determines its vibration modes is influenced by the height of the tapping above the pipe crown into which the probe locates and is held. For the calculations shown this tapping length was set to 200mm. This represents a value typical of a 50mm BS gate valve screwed into either a drilled and tapped boss, or a collar mounted boss. However, an operator may install the probe direct into a tapped pipe in which case the tapping length could shrink to 50mm. Alternatively, where high pressure pipe work is encountered, the fitting sizes and especially the size of the required isolating valve may extend the probe location point to 350mm above the crown of the pipe.

Figure 6.38 illustrates the sensitivity of tapping length using the range of values discussed above for 250, 600 and 1200mm pipes.

As seen, the limit velocities at 200mm tapping length, without applying a confidence limit, are respectively 3.5m/s, 1.5m/s and 0.6m/sec for the 250, 600 and 1200mm pipes. Adding the confidence limit as per earlier practice further lowers the limits to 2.1, 0.9 and 0.34 m/sec.

Such values of velocity are noticeably low in the context of the pipe sizes and flowrates representative of WISPY meters undergoing verification and illustrate that the choice and size of pipe tapping are important factors in determining probe application limits.

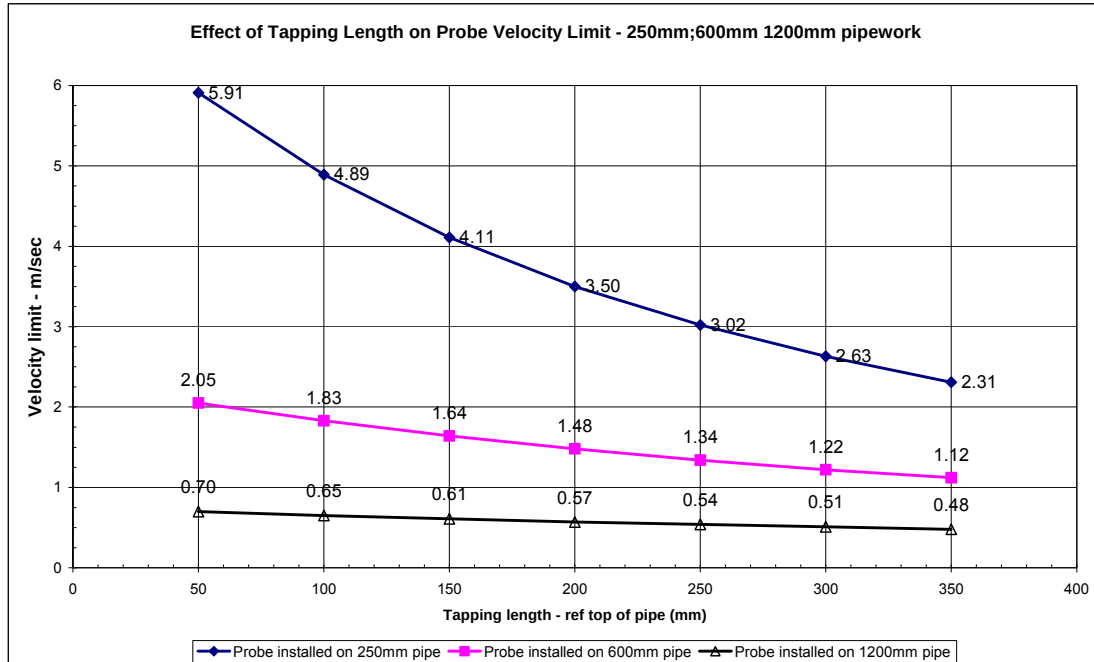


Figure 6.38: Effect of tapping length on probe velocity limit – 250, 600 and 1200mm pipe work

6.4.5 Vibration limit when profiling 1200mm pipe

The opportunity to profile a large pipe, >1000mm, in an operational context could not be arranged because the available locations were found to run at high pressures, 15bar and above. Insertion probe techniques are inappropriate in these circumstances due to Health and Safety considerations. An opportunity arose, however, to profile the pumped 1200mm (1195mm exact inner diameter) line in ABB’s factory and this was undertaken with a 2m battery probe of the type which had been modelled for vibration.

Two runs were made, one at 0.55m/s and the second at 1.00m/s, generating Re values of 655,000 and 1,195,000 or 2.07 and 3.77 times that at Hams Hall. In regard to vibration limits the first run lay within the manufacturer’s “safe” zone. The higher flow fell outside the manufacturer’s “safe” zone regarding vibration over the full insertion range.

Interpolating from the manufacturer’s limit data indicated that vibration would take hold at around 1000mm insertion depth. In contrast, the revised thesis calculations forecast vibration to become a problem at between 550mm and 800mm, with the difference depending upon the value chosen for the derating factor.

Figure 6.39 shows the summary of the 13 point profile recorded with the developed software. The software allocates names to the individual points, from P1 through to P13. P1 is the position measured at the far wall with the numbers progressively increasing to point P13, the position closest to the top of the pipe. P7 represents the

centre line point and P2 and P12 are the points for which, along with P7, the software undertakes repeated measurements in order to assess data quality.

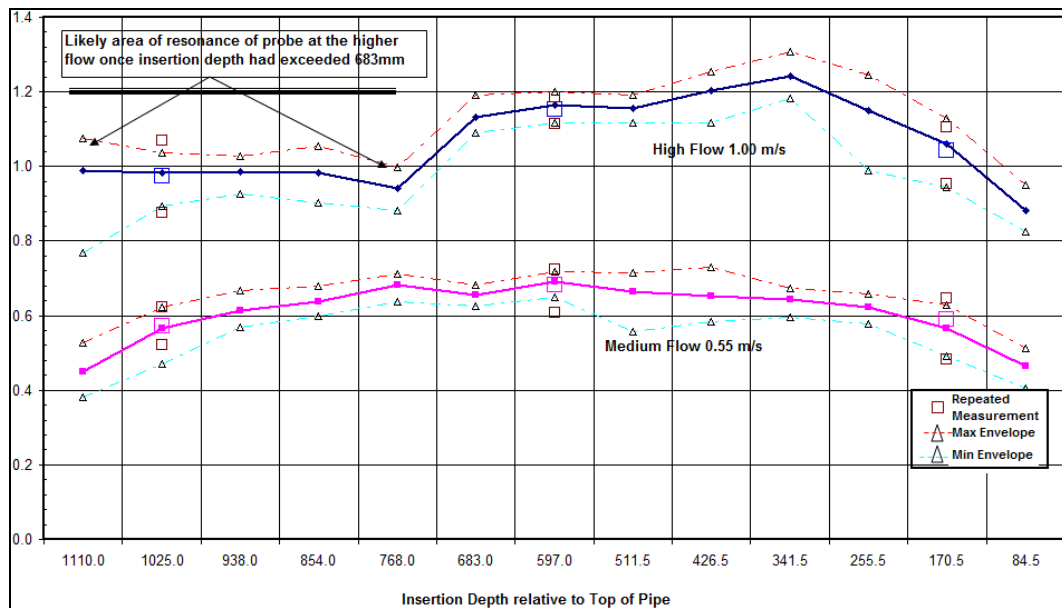


Figure 6.39: Mean velocity for high and medium flow against insertion depth

The output of the profiling software showed that, at the lower flow of 620 l/sec, 0.55 m/s bulk flow; the profile factor, F_p , was 0.7831, with all data measurements being successful and there being no exceedances of the in-built noise, stability and reproducibility presets.

At the higher flow of 1.00 m/s the data collected from the near wall (top-of-pipe) profile positions was similarly within limits. However, on the opposite side of the pipe between P1, the initial far wall point and P5, (427mm retracted from the far wall or 768mm into the pipe), the velocity recorded by the probe is flat at just under 1m/s. This was judged unlikely to be representative of the true local flow velocity because of the distortion of the profile shape when compared to that seen at the lower 0.55m/s run.

Examining the general shape of the 1.00 m/s profile curve it can be seen that after P10, (855mm retracted from the far wall or 340mm into the pipe), the transduced flow velocity becomes gradually offset and decreases until at P5 the velocity signal becomes invariant with insertion position; “saturated”. This characteristic behaviour could be expected if the probe tip is sensing a velocity signal generated from the combination of a vibrating probe added to a second but relatively smaller flow related component.

Physically it was possible to feel the significant vibration of the probe stem throughout the higher flowrate test although manual feedback could not identify when the vibration “set-in”, whether at P5 or P6. Insertion beyond the centre line, P7, gave rise to levels of vibration which subjectively must be classed as “severe” and gave rise to considerable operator concern.

6.4.6 Discussion of the 1200mm profile test and probe vibration limits

- a) Examining figure 6.39, the data recorded from the measured 1200mm profile, taken alongside the physical observation of the probe, suggests that when choosing between the three possible limiting insertion length limits, (i) that published by the manufacturer (ii) the base thesis recalculated value and (iii) the recalculated thesis value modified to provide a confidence band, that stated by the manufacturer of approximately 1000mm, is least reliable.
- b) The recalculated “safe” working limits (given in this thesis) span a considerable range, equivalent to insertion depths from 550mm to 800mm for a 1200mm pipe. This range is in turn dependent upon the value of the confidence factor used.
- c) If, for the 1200mm pipe the “safe” working limit is chosen circa 725mm, hence matching the observed change in profile which lay between P5 and P6, then a confidence factor of nominally 10% would need to be applied to the thesis recalculated limits of figure 6.37. On the basis of the available test data this is not unreasonable.
- d) In summary, the battery EFM insertion probe design should not reference the existing manufacturer’s insertion depth/velocity limits but should make use of the recalculated thesis limits utilising a confidence factor of 10%.

6.4.7 Summary of probe fundamental vibration and velocity limits

- 1. The practical limits of using a cantilevered probe are reached more rapidly than the manufacturer has stated in the published probe application advice.
- 2. The evidence at the present time, derived from detailed profiling of ABB’s 1200mm line, is that the manufacturers’ recommendations regarding insertion limits and flow velocities are incorrect and underestimate the onset of vibration.
- 3. Limitations imposed from probe vibration are more significant than previously assessed due to the lack of operating margin values within the published by the manufacturer.
- 4. Probe vibration calculations should be further investigated and modelled more elegantly in order to refine the present thesis recalculated limit values.

7 INVESTIGATION OF THE MEDIUM TERM PERFORMANCE OF BURIED BATTERY EFM METERS

7.1 BACKGROUND AND OBJECTIVES

As part of the introduction of the battery EFM technology a number of companies pursued the use of battery powered meters in areas linked to regulatory reporting, including water demand monitors. Previously only mechanical metering had been used to acquire this type of key performance data, which underpins the assessment of regulatory demand and/or leakage statistics. However, the inherent loss of meter accuracy which occurs with mechanical meters over time had prompted the use of the battery EFM's, which were claimed to retain their calibration and stability over long periods.

Severn Trent Water's adoption of the battery EFM technology to measure flows in its Small Area Monitor (SAM) offered the opportunity, 5 years after installation, to examine the regulatory and technical issues arising from the adoption of the battery technology and to assess the projected performance advantages of EFM metering.

The aim of the SAM field exercise and analysis was thus threefold, namely:

- (a) to review and, where possible, quantify the quality of the battery EFM data reported for regulatory purposes after 5 years of operation;
- (b) to check the calibration stability of the battery technology and
- (c) to develop an evidence based case for ongoing meter maintenance and verification requirements, focusing on battery EFM designs.

The work described covers (1) the history, development, specification and design of the SAM [44]; (2) a review of the SAM battery EFM performance, including identified weaknesses, approximately 5 years after its installation and (3) the excavation and recalibration of one of the SAM battery EFM meters, 6 years after installation.

7.2 DEVELOPMENT OF A BATTERY EFM "MONITOR" AND THE LINK TO UFW/NRW POLICY

As a prelude to the design of the SAM, STW had created in 1984 a Domestic Consumption Monitor (DCM). This generated knowledge of water use across the range of socio-economic groups within the company's area. It was built on data derived from individual households, measured through daily logging of the pulse outputs of 15mm mechanical meters. Such knowledge pertaining to individual households forms the lowest level of the water balance table and is essential in the accurate calculation of unaccounted for water (UFW), now generally referred to as non revenue water (NRW).

However, a DCM is only able to provide assessment of customer demand as measured at the point of supply, which in the case of STW is internal to each of the households. This necessarily misses the contribution from leaking pipework feeding the household from the distribution pipework located in the road. To attempt to assess the size of this

loss and to increase confidence in the global DCM results the concept of a Small Area Monitor was created.

The SAM concept is based around measurement of a number of cul-de-sacs, i.e. single ended sections of the distribution network feeding a limited number of households. The philosophy is to measure the inflow to the cul-de-sac, understand the pipework materials of the network within it, the nature of all the dwellings and the occupants within the households supplied and then, by referencing the DCM statistics calculate the leakage occurring by subtraction of the aggregated DCM volumes and that recorded by the single SAM meter. This is shown in figure 7.1.

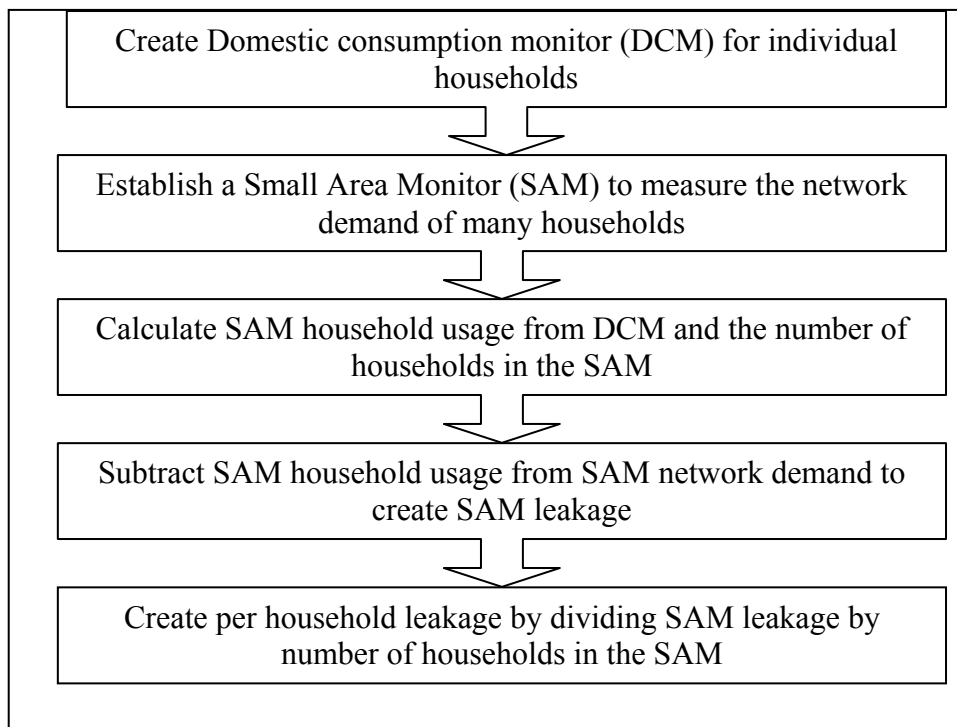


Figure 7.1: Relationship between DCM and SAM monitors

A view can then be drawn on the different leakage rates associated with the pipework materials and fittings located between the SAM meter and the household meters. These differences feed into the UFW/NRW calculations.

STW's SAM was created by selecting approximately 100 locations across the STW network, with each feeding discrete areas of between 50 and 100 properties. Where a single feed could not be engineered two battery EFM meters were installed and a net demand was calculated. As part of the selection criteria commercial customers were avoided and a target set to limit metered domestic customers to less than 10% of the SAM properties. All water-mains materials were included, as were all socio-economic groupings based on the ACORN classification. This is a standardised means of classifying areas according to various census characteristics; both geographic and demographic [86]. Installations were spread evenly across all Severn Trent's administrative boundaries or "counties", with the intention of smoothing localised consumption patterns. Further background is contained in work from UKWIR [87].

7.3 SPECIFICATION AND DESIGN OF THE SMALL AREA MONITOR

7.3.1 Installation design to minimise EFM sensor signal noise

Laboratory testing at Cranfield had shown that the battery EFM performance conformed, within the limits of the testing regime, to the manufacturer's specification. However, the expected flow profile for a representative SAM application included extended periods of operation within the lower part of the specified EFM accuracy range, where the effects of noise, electrical or hydraulic, may affect the quality of the data. This knowledge affected the overall design philosophy which was deliberately made technically more conservative. This outlook was reinforced as all EFM sensors were to be buried, minimising post installation changes.

Moreover, intrinsic to the SAM application was the need to ensure and demonstrate accurate and traceable flow data because of the comparative use to which SAM data is put; namely, contrasting similar demand profiles with inherently small differences attributable to the local varying levels of leakage.

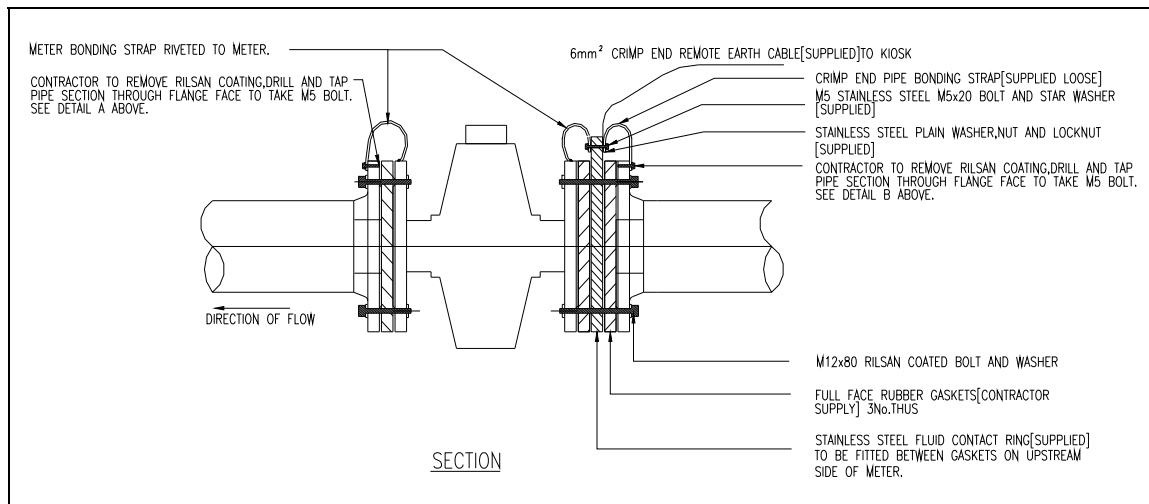


Figure 7.2: Detail of SAM meter installation and electrical bonding

Great care was therefore taken to install the battery EFM meters in the correct hydraulic and environmental conditions and to ensure that bonding of the meter sensors was as advised by the manufacturer. Figure 7.2 illustrates the detail of the bonding arrangements implemented.

7.3.2 Standardising the EFM hydraulics and access

The minimum number of straight upstream diameters specified by the battery EFM manufacturer in order to achieve the stated performance was five. However, in view of the lack of knowledge of upstream conditions and the need to standardise on relative performance it was decided to extend this upstream length to the maximum practical, 1000mm, equivalent to 12.5D.

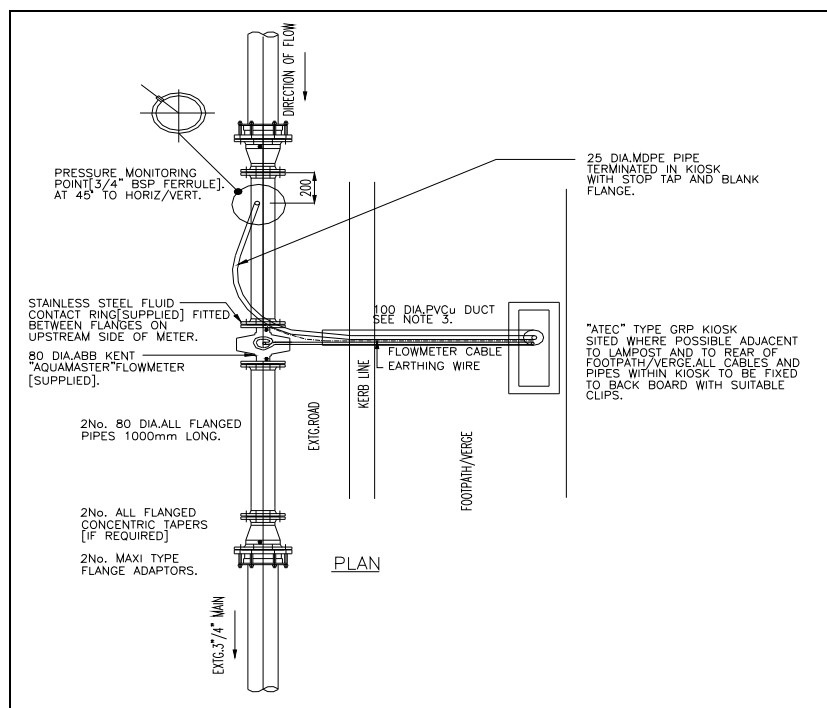


Figure 7.3: Detail of SAM pipework arrangements

Each of the 100 individual EFM's was then pre-assembled on a workbench before being installed as a pre-formed, standardised section. Two stainless earthing rings, providing the necessary fluid bonding, were included on all assemblies and a separate earth strap connected from the flow tube (sensor) to the transmitter housing to complete the bonding arrangements.

In the light of past experiences care was taken to avoid damage to the EFM sensor as a result of manual handling by the civil engineering contractors, minimising all physical shock which can result in shifting of the EFM calibration.



Figure 7.4: SAM Sensor installation in trench prior to burial

A pressure tapping was installed on each installation to enable logging of diurnal pressure variations via a separate transducer connected to the spare channel of the attached flow logger.

Logging equipment, including the meter transmitter, was sited above ground in roadside cabinets. This made for greater ease of electronic reading the transmitter and data logger; a Technolog Babylog 3, single channel 128k datalogger [88]. Choice of a roadside cabinet later facilitated a remote read solution implemented on a selected number of meters three years after commissioning.

The environmental protection afforded by the cabinet precluded the need to pot the connection box of the transmitter, simplified the exchange of batteries when required and gave access to all of the wiring connections. This latter feature proved very useful when investigating the EFM performance 5 years later.

All the meters were logged for both forward and reverse flow. Whilst this was essential for sites having two meters measuring inflow and outflow, it was also helpful when diagnosing malfunctioning software.

Further details of the installation are provided in reference [44].

7.4 5 YEAR AUDIT OF SAM EFM PERFORMANCE: INCLUDING THE EFFECTS OF EXCITATION CHANGES

The role of the work undertaken in auditing STW's Small Area Monitor (SAM) is of importance in relation to the "June Return" data submitted annually to the Regulator OFWAT by STW. It represented the first comprehensive audit of the accuracy, stability, data integrity and developing maintenance requirements of the battery EFM's which had been chosen to replace mechanical meters in the monitor.

7.4.1 Technical scope of 5 year benchmarking of battery EFM performance

To examine the state and quality of the small area monitor (SAM) flow readings through an in-depth audit, using digital time-series data acquisition, covering:

- 1) the hardware: including the buried sensor, the EFM transmitter and interconnecting cabling;
- 2) the software version: as programmed ex factory;
- 3) the meter configuration: including all 350 factory set parameters;
- 4) datalogged records of dynamic flow, allowing:
 - an assessment of the measurement performance
 - the generation of benchmark data

leading to an understanding of the quality and performance of the battery meter technology after 5 years and the opportunity to identify improvements.

The on-site physical checks required to deliver these objectives included:

- (i) electrical testing of the sensor coils;
- (ii) measurement, using the transmitter indirectly, of the sensor electrodes;

- (iii) recording of all the internal transmitter parameters, including 20 key values and 300 general values. The specific parameters targeted were: software version, settling time, flow cut-off level, date and time, serial number and alarm states for sensor and electronics
- (iv) insulation and electrical testing of all the cabling between transmitter and buried sensor
- (v) measurement of battery state
- (vi) real-time logging of the flow at different field excitation frequencies and sensor pre-amp power conditions. This required six consecutive 1000sec runs operating in the two different modes
- (vii) calculation of statistics relating to the flow signals recorded in (vi)

7.4.2 Requirement to develop an EFM audit record

It was observed at the start of the work that a number of assumptions had been made by the users of the SAM data. These brought into question the validity of the data chain. The two most common assumptions were (a) that the EFM meter calibration performance had been verified in situ, on an annual basis and (b) that the original EFM set-up information was held “elsewhere”, whereas research uncovered the fact that no such archive had been specified as part of the installation contract. The need therefore arose to create a database capable of combining the administrative and the technical elements associated with the 96 EFM meters comprising the SAM.

Due to the large number of parameters and the projected volume of real-time data which was to be gathered, a standard format was developed. This covered the site details, the EFM display status, plus two further record sheets relating to the measured dynamic meter performance. When integrated these resulted in a composite and credible technical description of the SAM, in line with the importance of the Regulatory aspects of the use to which the SAM data was being applied.

7.4.3 Data acquisition method and software for SAM recording

An improved data acquisition tool, developed following the Cranfield laboratory testing, used in conjunction with separate software from ABB [89], allowed detailed information to be gathered from the 96 SAM installations. Figure 7.5 illustrates the design of the software.

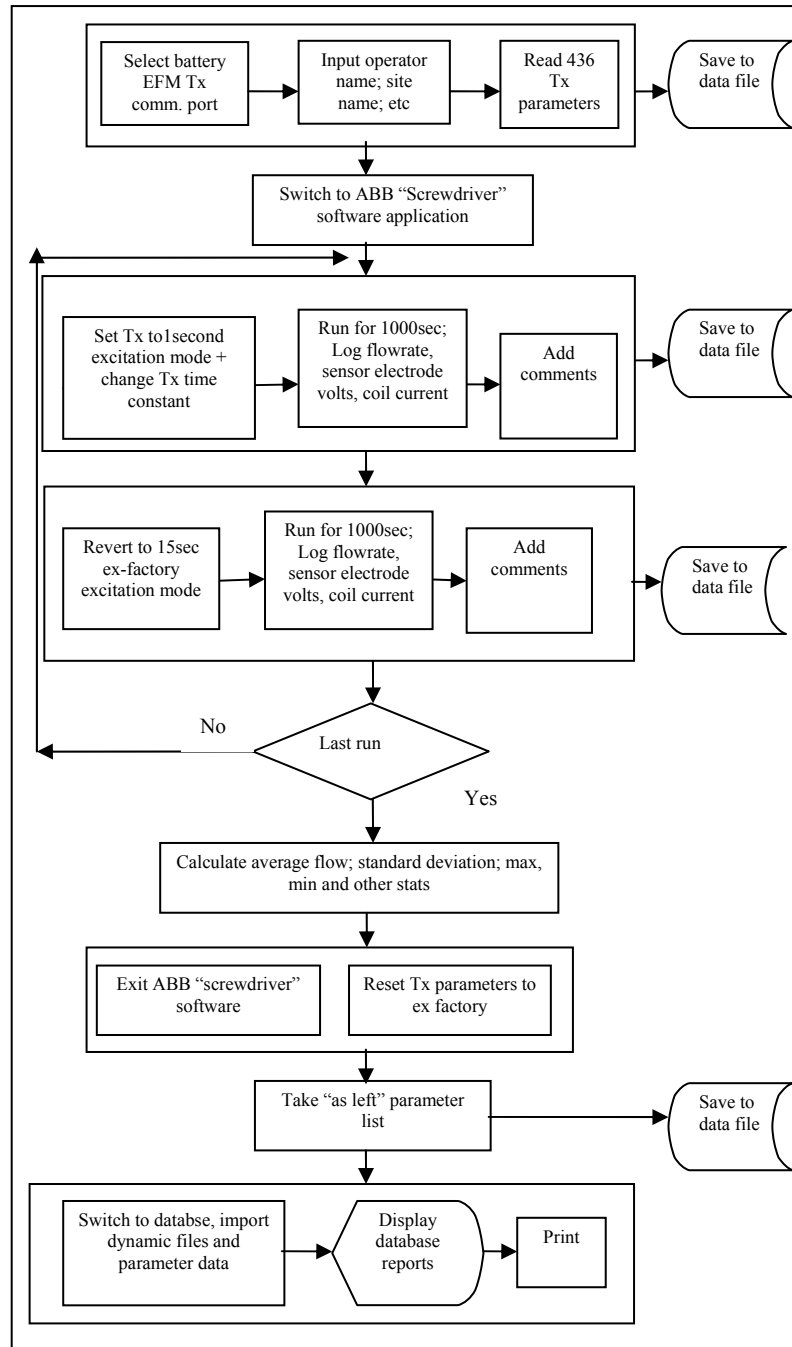


Figure 7.5: SAM field data acquisition software functionality

To achieve 1 second data logging, needed to capture the maximum field refresh rate of the battery EFM design, use was made of a proprietary software package from ABB [89]. This was incorporated into a purpose built routine along with a Hyperterminal [53] based program to read the EFM parameters.

As shown, an excess of 300 parameters was recovered from each battery EFM in order to be able to either (i) confirm correct operation and set-up, or, (ii) to trace any fault condition encountered. Moreover, use of dynamic data recording allowed a detailed view of each individual meter to be constructed.

7.4.4 Dynamic flow signal recording and data quality

The calibration work at Cranfield had highlighted the importance of recording the digital flow signals. Subsequent site work at Chaddesley Corbett, using the probe variant, further showed that battery EFM performance was significantly altered over the short term by changing the rate of the field excitation from 15seconds, as set by the factory, to 1second.

For the SAM work it was decided to contrast these two modes, on the premise that under the quasi-stable bulk flow conditions present with operation of the full bore version of the battery EFM, it would be possible to highlight differences in the quality of the measurement data.

The principle difficulty for the owner of the SAM data lay in validating the ongoing quality of the results which had been collected from the meters since 1998. Initially, there had been no perceived problems but, as time proceeded, doubts concerning a variety of battery EFM units arose. Lack of diagnostic tools meant that only the historic pattern of flow readings, interpreted by local knowledge, were of use in forming a judgment concerning the validity of the data. Thus development of the dynamic flow recording approach was targeted on providing a means to objectively assess the quality of the EFM data and thereby allow only validated quality data to be used in the regulatory “June return”.



Figure 7.6: Site set-up for SAM 5year audit showing data collection system

7.4.5 Results of the dynamic flow recording

Figures 7.7 and 7.8, taken with tables 7.1 and 7.2 below, show an example of a standard set of records produced by the software. The EFM shown is that for SAM 6875.

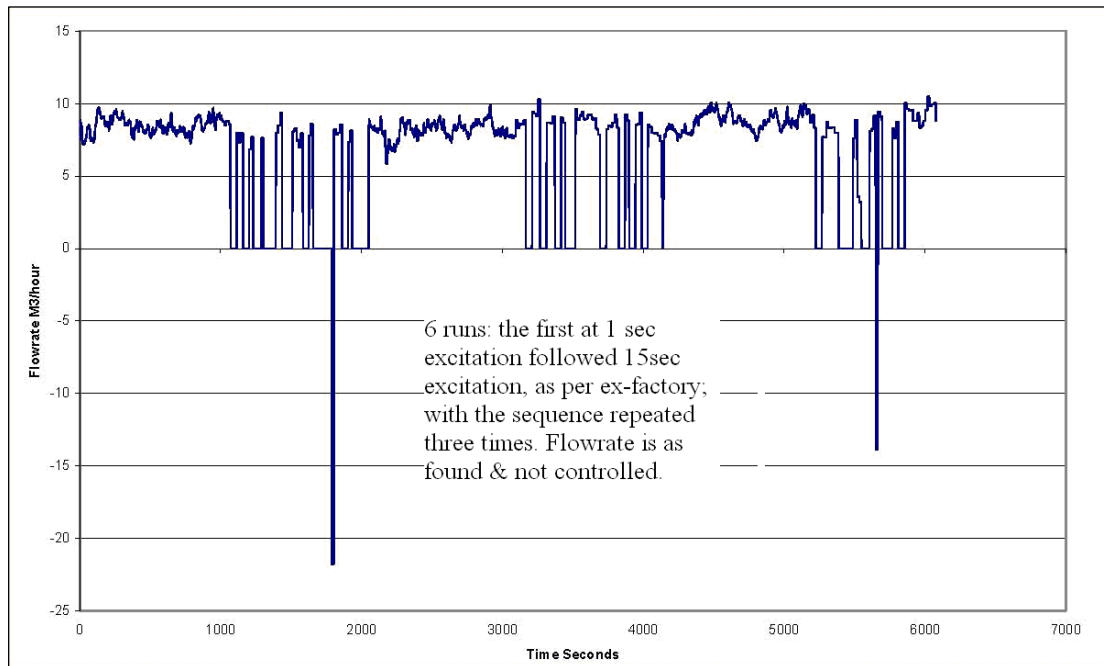


Figure 7.7: Flow performance under different modes

Figure 7.7 illustrates one complete test run controlled by the software. The single run incorporates three differing excitation periods, repeated alternatively, during which the excitation and refresh rate have been set either to 1 second or to 15seconds.

As is evident, the change in excitation mode markedly alters the response of the battery EFM. When in the ex-factory mode, the signal can be seen to suffer large excursions and is not stable over the period of the recording. After reprogramming to alter the period for which the pre-amp was powered plus changing the field refresh frequency, the meter can be seen to operate in a stable state.

This characteristic behaviour was seen on many of the buried meters. Observation indicated that it was a function of the sensor and that in certain cases changing the mode had no discernible effect on the values measured during the flow recording; other than to reduce the number of samples by a factor of 15, as would be expected.

Quantifying Dynamic performance and meter setup

As a means of quickly identifying faulty operation visually, the use of differing excitation modes proved highly successful. The need to quantify the differences shown visually in figure 7.7 was addressed using a second, simple, graphing approach.

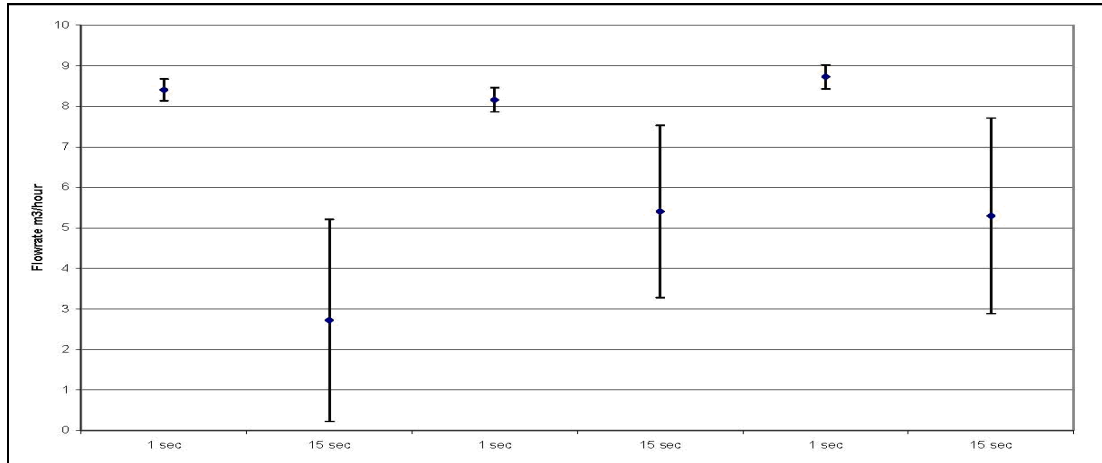


Figure 7.8: Average flow for each data / mode period. Shown with 2* std deviation limit i.e. 95% coverage factor

By plotting the average flow generated from the raw digital data and displaying this with the expanded uncertainty limits, represented by twice the standard deviation of the particular dataset, it was possible to illustrate both the change in absolute value for the measured flow, alongside the statistical spread of the logged data, caused by alteration of the test mode and excitation. Figure 7.8 illustrates this.

Each SAM meter was assessed in the above manner, with an accompanying summary table of the logged data performance. This is illustrated in table 7.1.

		Average	Stdev	Range	NSE
Run 1	1 sec	8.40596	0.543559	2.542977	6%
Run 2	15 sec	2.715786	4.991041	31.17175	184%
Run 3	1 sec	8.159138	0.590125	3.31658	7%
Run 4	15 sec	5.402998	4.2567	10.28505	79%
Run 5	1 sec	8.729266	0.595637	2.66195	7%
Run 6	15 sec	5.294244	4.828925	24.37734	91%

Table 7.1: Table of meter performance with different excitation modes

To complement the graphical analysis and create a comparative set of records spanning the complete 96 installations, suitable for comparison, the details of each individual meter were grouped and placed into a database developed for the purpose and linked to the data collection.

Table 7.2 illustrates the format adopted. The scope of the details recorded included parameters which were user settable and could therefore have been changed over the 5 year period. The most important of these and the one which had direct relevance to the accuracy of the regulatory data was the pulse output sensitivity.

Description	Value	Units	Description	Value	Units
Software Version	V1.02		Coil Current	0.0567753	
Flow Sensor ID	0.01		Flow Preamp Gain	3.00081	
Flow Sensor (Batt)	0.63569		Empty Pipe Zero	0.01	
Flow Sensor Contract No	V/20017/3/3		Flow Sensor Bore	80	
Pulse Output Units	1l		Flow Sensor Zero Low Current	-10	
Pulse per Pulse Output Units	1		Flow Sensor Setting Time Constant	350	
Calibrated Velocity	0		User Flow Sensor Cal	1	
Raw Tx Velocity	0.00662782		User Flow Sensor Zero	0	
Left Electrode Resistance	4.69407		Flow Cut Off Low	9	
Right Electrode Resistance	4.75766		Flow Sensor B-H Coef B	0	
Sig A Voltage	0.281183		Flow Sensor B-H Coef A	0	
Sig B Voltage	0.269771		Display Timeout	0	
Direction	0 No		Error	512	

Table 7.2: Summary statistics for each data collection period

Elsewhere, and for completeness, the full list of EFM parameters, recorded automatically by the software, was filed for traceable comparison with manufacturer records.

7.4.6 Categorising field measurements - Pass/Fail recommendations

The difficulty in categorising the individual 5 year SAM meter performances lay in the lack of traceable evidence of original performance, either in the factory or post installation. Without such objective data one is unable to derive a sound measure, related to conformance to the original claimed specification, for the absolute performance of the meters.

The approach adopted was to reference the changes seen in the calculated statistics when altering the excitation mode and to link those findings to STW's flow records. So, for the meter example given above, table 7.3 shows the linked recommendations field taken from the database record advising that the meter is not working properly, despite the fact that readings which Severn Trent have been using were considered "normal".

The results indicate that the meter is not working properly. The meter gives reasonable patterns in 1 second but keeps dropping to zero whilst in 15 second mode. The Average appears to be inflated by this and the Standard deviation of course increases. Historical Pmac data shows that the forward flow appears normal with a diurnal pattern, however the minimum flow is 4 m3/hour. The reverse record shows very little reverse flow just small spikes. The totalisers in the flowmeter did not confirm the Pmac data showing the reverse total as 56123 m3 in a forward total of 135476 m3. The transmitter was changed for the duration of the diagnostic tests and then the version 1.-02 was replaced and the system left working as normal.

Table 7.3: SAM 6875D assessment advice

7.4.7 Contrast between the technical assessment and the water company's meter assessment.

As part of the audit methodology the technical measurements relating to the battery EFM were compared with the assessment of the same meter by the operator, prior to the investigation. This highlighted the difference in the operator's view of the battery meter population, arrived at from familiarity with the assumed network flow pattern, and the view derived by objective recording of the meter output under alternative excitation modes.

The differences are summarised as follows:

- in 33% of audits measurements indicated that the meter was not performing correctly;
- in contrast, the operator's view of the same 33% was that the data was satisfactory;
- in 55% of all meters the operator and audit views coincided;
- in 12%, the state of the meter had to be classified as indeterminate because sufficient meaningful measurements could not be taken.

7.4.8 Summary statistics for the SAM audit

The following is a summary of the findings derived from analysis of the meter setup parameter data combined with comments relating to site factors:

- 76% of meters had the original ex-factory V1.02 firmware running 5 years after installation. The manufacturer subsequently stated that V1.02 was "susceptible to noise"; 24% had a different version of firmware ex-factory;
- 20% of meters had a settling time which was inappropriate to the SAM application;
- 34% had the incorrect date;
- 10% had the incorrect time;
- 30% had the serial number incorrectly programmed;
- 93% incorrectly showed empty pipe and sensor alarms but were functioning correctly in contradiction to the alarm status;
- Overall 30% of the battery EFM meters were judged to be operating in a satisfactory manner and likely to be in conformance with the specification;
- All the buried sensors appeared to be intact, as determined from insulation measurements;
- 10% of the meter audits could not be fully completed because of site problems.

7.5 EXCAVATION, EXAMINATION AND RECALIBRATION OF A 6 YEAR OLD BATTERY EFM METER

As commented earlier, the difficulty in categorising the individual 5 year SAM meter performances lay in the lack of traceable evidence pertaining to either the ex-factory or post installation performance. The obvious documentation would have been offered by the meter's calibration certificate but Severn Trent had not requested these when ordering and no records were available within the company. Thus, the opportunity was readily taken when it was possible to excavate and remove for re-calibration, one of the 96 SAM meters.

7.5.1 Removal and disassembly of SAM metering section

The extensive work on in-situ signal performance, which had highlighted anomalous performance, contained a fundamental weakness. Although the credibility of the recent measured data could be examined and debated, the key question as to cause and effect and the role of possible long term meter drift could not be answered. The solution lay in the removal and recalibration of one of the original batch of SAM battery EFM meters but STW were not open to such action principally because of the: the impact upon customer service of the loss of supply which would be caused.



Figure 7.9: Excavating SAM meter sensor 6891



Figure 7.10: Removing SAM meter sensor 6891 from Manor Place

Fortunately, the company's planned programme of mains renewals generated a unique opportunity to take out one of a pair of meters without disrupting customers beyond that which had been scheduled. SAM meter 6891, Manor Place, was a standard unit installed as all other 96 meters in the SAM programme. Removal was carefully supervised as shown in figures 7.9 and 7.10 and the complete meter assembly taken to ABB's factory. Figures 7.11 to 7.14 show the assembly in the manufacturer's laboratory.



Figure 7.11: Unburied 6yr old SAM metering section - split and with protective tape removed



Figure 7.12: Second half of metering section – showing smooth internal bore



**Figure 7.13: Meter condition
- after removal of protective tape**



**Figure 7.14: Pressure tapping on end
of metering section**

The key point of note is the outstanding condition of the meter assembly after 6 years of being buried, made possible because of the detailed corrosion protection originally specified. Both externally and internally, the meter and the pipework can be seen to be close to its ex-factory condition.

7.5.2 Factory re-calibration results and failure analysis

The aim in returning the meter sensor to the factory was to undertake an ex-field condition meter calibration. This was to be compared to that originally undertaken. However, the meter cabling, as excavated, prevented direct connection to ABB's production calibration equipment. To overcome this it was necessary to access the pre-amp board, which is contained in the sensor head box, by carefully removing the elastomeric compound in which it had been potted, without damaging the board.

ABB advised that there was a known problem with the 1998 design of pre-amp board installed in the sensor head and suggested its replacement prior to calibration. However, this was not done immediately as it was essential to record the meter performance in the "as found" condition in order to establish performance traceability.

The following nomenclature provides the key to the calibration results which are shown in figure 7.15. The calibration sequence was "A" followed by "B" then "C":

- a) Calibration "A" – is that taken in the excavated "as found" state in November 2004, complete with the original production pre-amp board. The calibration is over an extended flowrate range as compared to the range over which the same battery EFM sensor had originally been tested in 1998;
- b) Calibration "A2" – represents the 2004 "as found" results from calibration "A", re-plotted graphically with the zero offset error of calibration "A" corrected mathematically;
- c) Calibration "B" – is the performance obtained after replacing the 1998 pre-amp board with the more modern design but still programmed with the "as found" 2004 pre-amp values;
- d) Calibration "C" – is the updated calibration obtained with the new pre-amp board calibrated over the extended flowrate range.
- e) 1998 calibration results. These are the original calibration data – note that there were only four points with one flowrate point repeated.

The utility of adopting the step-by-step calibration sequence was that it allowed separation of the hardware/firmware changes from changes which were introduced through changing the range and the methodology of the calibration.

7.5.3 Re-calibration results for excavated battery EFM SAM 6891

The calibration certificates and data for the recalibrations undertaken at the factory are available in the I+P Services test report on recalibration of SAM 6891 [90]. Because the meter sensor was more than five years old the manufacturer no longer held the original calibration information. Fortunately, a copy of the SAM calibration data had been made and held by an external party making it possible to compare the original and the recalibrated results.

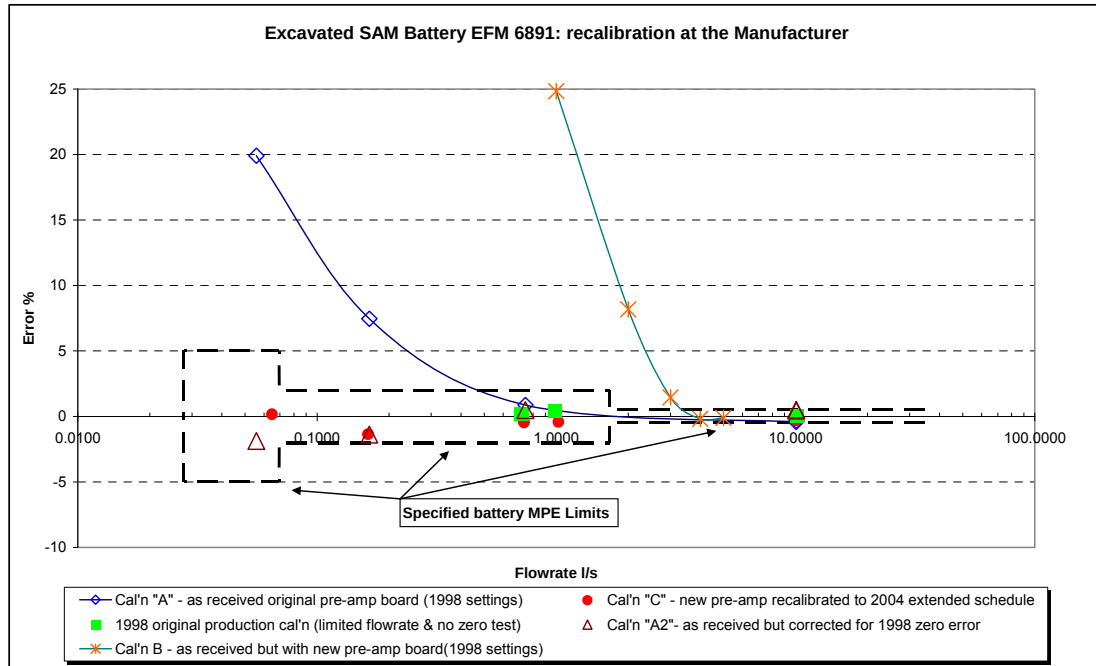


Figure 7.15: Summary of ex-field battery EFM calibrations - SAM Meter 6891

As figure 7.15 shows, the calibration differences between the 1998 and 2004 tests were significant showing that the meter, as installed in Severn Trent's SAM, had been outside the 2% MPE limit, of both the ISO and the manufacturer's own specification, below approximately 0.4 l/sec; equivalent to 1.44m³/hr.

For the given pipe size of 80mm, 0.4l/s equates to a bulk velocity of 0.08 m/sec. This velocity is approximately fifteen times larger than the minimum velocity stated by the manufacturer at the battery EFM's minimum specified flow. It is clear, therefore, that conformance with the meter specification should not have been lost at this relatively high flowrate.

Source of the errors due to the original battery EFM calibration

The inference from the shape of the graph for calibration "A" is that the zero point of the original calibration had been in error. The reason for this can be deduced as follows: the original calibration range did not match the published specification; therefore the manufacturer relied upon the linearity of the design to be able to extrapolate the zero point from the straight line drawn through the three production calibration points. As the graph of calibration "A" shows, when tested over the full flow range, this extrapolation and the inherent zero error resulted in errors outside the published MPE.

When the zero error of the "as found" calibration "A" is corrected mathematically, one can observe in the "A2" curve of figure 7.15 that the meter, originally only compliant over the upper range where it had been calibrated in 1998, becomes compliant with the published MPE limits across the full flowrate range.

This demonstrates within reasonable doubt that the battery EFM sensor design does not have an intrinsic problem of drift as removed from site, (associated with the original

1998 pre-amp board or sensor hardware) i.e. that despite being inaccurate, the evidence is that the medium term EFM sensor stability appears satisfactory; based on this one sensor.

Effect of swapping the 1998 sensor pre-Amp board for a 2004 board.

Curve “B” in figure 7.15 illustrates the effect which removing the old pre-amp board and introducing into the sensor a new, post 1998, design had upon performance. The errors shown in curve “B” are similarly large to those of the original in “A”. However, this is because of the same uncorrected zero offset introduced by having the new pre-amp board programmed with the 1998 data. Therefore, calibration curve “B” illustrates a similar, badly divergent, error characteristic to that of the original 1998 pre-amp board.

To prove that the differences between curves “A” and “B” were a function of the individual board setup/gain characteristics and not changes in the EFM sensor, calibration “C” was undertaken using an increased number of test points. These points covered a much extended Reynolds number range compared with the original 1998 calibration and include operation into the transition region between turbulent and laminar flow. This calibration thus programmed the new pre-amp board with data from the revised flowrate test schedule, the data for which is shown in table 7.4.

Flowrate l/s	Error %	Error mm/sec	Reynolds number in sensor throat
Calibration "C" - extended 2004 flowrate schedule			
0.0648	0.16	-0.020	1644
0.1634	-1.35	0.440	4150
0.7318	-0.38	0.555	18600
0.7332	-0.45	0.657	
1.0216	-0.41	0.836	25900
10.0400	-0.15	2.785	
10.0600	-0.3	6.168	255000

Table 7.4: Updated calibration sequence for excavated ex-service sensor SAM 6891

As the table shows, the improvement relative to the 1998 meter calibration result, figure 7.15, is marked, pulling the meter curve into full compliance with its published specification.

7.5.4 Establishing traceable accuracy: calibration schedule, run time considerations and error summary

The improvements seen in table 7.4 are at the expense of considerable additional time on the calibration rig; 3800 seconds calibration run time for the 2004 thesis schedule, in contrast to 800 seconds for the 1998 factory production schedule.

This increase in calibration time, almost 5:1, is very expensive for a manufacturer but the evidence objectively demonstrates that without the lower range flowrates and extending test times, the production calibration team cannot demonstrate the level of traceable performance necessary to meet the published specification; for this particular battery EFM product.

In summary, the 6 year recalibration of the 1998 sensor whilst exhibiting the good reproducibility of the intrinsic battery EFM design, was non-compliant with the published specification. The margin by which the errors exceeded the published MPE was large, with the exception of the highest flowrates.

These errors will have significantly distorted the aggregated volume totals which will have been submitted to the regulator over the six years of operation of this and the other SAM battery EFM meters. In effect, they will have distorted the basis of unmeasured consumption and leakage components of Severn Trent Water's water balance submission due to poor data quality.

The cause of the errors was the failure to adequately span the specified operating range, which extends into the near laminar region, when the initial calibrations were undertaken. However, this is not a reflection on the capability of the battery EFM technology but on the rigor with which calibration was pursued by the manufacturer.

Note: Historically, due to the significant increase in rig calibration time which testing at the extended lower flows incurred, it was the case that the manufacturer had in 1998 actively chosen to minimise the number of runs at low flows. This had been primarily an economic and not a technical decision.

7.6 REGULATORY AND POLICY IMPACTS OF BATTERY EFM MEDIUM TERM PERFORMANCE FINDINGS

Consider the findings of the SAM audit and meter recalibration exercise grouped into four areas which impact on the regulatory process: maintenance; data accuracy; data integrity and meter calibration.

7.6.1 Maintenance

- The battery EFM, unlike its mechanical counterparts, requires consideration as an integral package comprising software and hardware elements. To date, any software component has been assumed to be static over the lifetime of a meter. The audit found this not to be the case for Severn Trent Water's small area monitor which used a battery EFM design. Such software differences were opaque to and not understood by the SAM operators.
- Battery EFM's are presently optimised, ex-factory, for longest economic life. However, changing the mode of excitation of a battery design, to achieve an improvement in performance, will change this. In the case of the SAM audited, changing the excitation mode was sufficient to improve the measurement performance of some meters which were not operating satisfactorily, but this was at the expense of the power budget. The balance between the performance and power thus has direct implications for projected battery life, the quality of data, the necessary maintenance regime and for the cost of ownership of the battery EFM.
- Unlike mechanical alternatives, buried, battery powered EFM's demand consideration of a 5 to 15 year maintenance provision; not 2-5 year swap outs. Regulatory guidelines must change to reflect this. Specifically, as with the WISPY meters which are acknowledged as key elements in the water balance equation,

verification of battery EFM 's needs to be properly provisioned where they are deployed within demand monitors, such as STW's SAM.

7.6.2 Data accuracy and quality

- Traceability, encompassing factory calibration plus a record of the “as commissioned” EFM parameters is required to build an accurate composite picture of the nature of the data being recorded.
- Software dependency was seen to be an influence on the quality of the logged data with differing firmware versions, pre-programmed by the manufacturer at the manufacturing stage, displaying different characteristics. A formal record is thus needed to be able to compare like with like when examining historic datasets and trends.
- Excitation mode has been shown to be critical to data quality and must be known to be adequate to be able to meet the required accuracy. This can only be done by making a record of the status of meter parameters.
- Data must be independent of the specific hardware and software implemented on a particular meter design. The audit illustrated that variability in data accuracy was linked to different software releases, a completely unacceptable position.

7.6.3 Data integrity

- The audit outcomes showed, unequivocally, that to demonstrate data integrity when using buried battery EFM meters one requires an ongoing programme of verification, in order to demonstrate year on year conformance with the original “as commissioned” performance.
- Because of the complexity of the battery EFM meter failures, complete loss of data became the only true indicator of meter status. For the particular case of STW's SAM, hardware failure meant the complete loss of all historic information rather than part loss up to the point of failure. This degrades the historic flow statistics and in order to maximise the regulatory data record it should be the case that the loss of the meter battery or hardware should not necessarily mean the loss of all stored data.
- The audit exposed the fact that, because of an inherent weakness in the data chain, made possible by the presence of operator programmable EFM features it was both possible and relatively common to corrupt the measured flow data. To assuage regulatory requirements concerning the provenance of flow data, one needs either:
 - a) to institute a formal verification process for battery EFM meters or;
 - b) to make formal provision of an independent and integrated audit capable of demonstrating meter performance.

7.6.4 Meter calibration

- It has been shown that the conformance with the manufacturer's performance specification cannot be assured if the factory calibration flowrate range is restricted; as was retrospectively found to have been the case with Severn Trent Water's small area monitor.
- Calibration must extend across the full field operating range in order for the battery EFM to measure validly and it is not acceptable to shorten the time of calibration, as was found to have been the case with the particular design checked after being buried for 6 years.

7.6.5 Water balance impact of calibration errors

- The error in calibrating all of the SAM battery EFM meters at low flows has led to a distortion in the reported regulatory consumption figures; which in turn has contributed to errors in the water balance. Although the exact volumes cannot be accurately determined because of lack of knowledge of the detailed SAM consumption profiles, an estimate of the impact on the total residential consumption is possible by referencing a separate, independent study. The study in question was undertaken by the same company, STW and consisted of exchanging fluidic meters with modern, extended range semi-positive displacement mechanical meters in 200 properties within their DCM. The DCM, as shown in figure 7.1, forms a link with the SAM in determining overall residential pipeline supply leakage.
- The study found that per household consumption volume changed by approximately 8% when changing the meter, with the likely reason being that the existing fluidic meter stops oscillating just below the specified minimum standard flow of 7.5 l/hr, whereas the modern mechanical meter continued measuring down to 2.5 l/hr.
- Given that an average SAM EFM meter measures the flow for approximately 100 properties, the flow range equivalent for this experiment lies between 0.25 m³/hr and 0.75 m³/hr. By referring to the calibration curve of the excavated battery electromagnetic SAM meter shown in figure 7.15, the battery EFM meter can be found to have been over-reading by between approximately 6 per cent and 18 per cent within this flow rate range.
- Overall the STW DCM study found that the total volume error was around 8 per cent when integrated across individual consumption profiles within the low flow measuring range. The impact of the SAM meters over-recording at low flows will therefore have been to generate an absolute error of between 0.48 and 1.44 per cent, relative to the true measured volume. (Derived by taking between 6% and 18% of the known DCM volume error)
- Seen in context, the impact of the SAM EFM metering calibration error on the total regulatory figures is more subtle. This is because the DCM will have historically been underestimating per capita household consumption by 8%, whilst the SAM will have been overestimating supply volumes by between approximately 0.5% and 1.5%. When combined to report the level of estimated leakage this will have had the effect of decreasing the leakage, although the SAM EFM meter contribution will have been smaller by the relative ratio between the underestimate of consumption by the DCM to the overestimate of the SAM by the battery electromagnetic meters.

7.7 SUMMARY

The objectives set at the start of the small area monitor audit work were threefold, namely: (a) to assess the quality of battery EFM data after 5 years of operation; (b) to check the calibration stability of the technology, and (c) to examine the ongoing

maintenance and verification needs of battery EFM's. A summary of the findings is set out below, with the formal audit conclusions being presented in chapter 10.

1. The quality of data collected by the SAM battery EFM meters was highly variable. The cause of variability had three major components:
 - a) sensor hardware problems;
 - b) a fundamental error in the factory calibration procedure;
 - c) mal-adjusted operator variables and;
 - d) differences in the transmitter firmware affecting performance.
2. As a representative example of the performance of battery EFM performance Severn Trent Water's SAM proved not to be typical. However, each of the specific SAM problem areas which the audit identified represents a generic influence factor for this type of technology.
3. Because of the spread of the problems affecting individual meters, it did not prove possible to quantify, overall, the quality of data. Nevertheless, one can state that, in the absence of objective checks on the accuracy of each meter's data, the flow statistics derived for the 96 SAM meters should be assessed under the OFWAT grading scheme as C3 or C4; unreliable, with an assessed accuracy of 5-10%.
4. The recalibration of one of the 96 SAM meters established that the measured flow was inaccurate and failed to conform to the published specification.
5. By exchanging the electronics board in the excavated sensor head it was established that the output of the battery EFM design had not drifted but that the absolute calibration of the sensor, programmed from new, was incorrect and that it was this that had lead to significant errors in the measurement of low flow data.
6. The impact of the SAM meters over-recording at low flows is to have generated an absolute error of between 0.48 and 1.44 per cent, relative to the true measured volume.
7. The manufacturer acknowledged the generic error inherent in the original factory calibration of all battery EFM meters manufactured up to that date. As a direct result the production calibration schedule was changed for this class of meter, providing additional calibration points to eliminate the existing problem in the transition and near laminar flow zones.
8. The evidence of poor performance collected during the SAM audit indicated that where buried meters have been adopted, it is essential to pursue some form of quality assurance or in situ audit/verification in order to create a reliable data record.
9. By comparing and analysing meter and data records the SAM audit highlighted a generic finding, namely that subjective, experience based, user assessment of flow measurements can lead to significant errors and result in loss of confidence in the overall dataset. Any system of audit/verification must therefore be based on objective technical tests and not on judgements founded on "knowledge" of a particular meter's expected flows.

8 DISCUSSION OF PRACTICAL AND POLICY IMPACTS ON REGULATORY PRACTICE

OBJECTIVE

This chapter takes the outcomes of the foregoing work and associates them with generic issues relevant to the OFWAT June return table 10 inputs and the subsequent calculation of unaccounted for water (UFW).

8.1 REVIEW OF THE ORIGINAL OBJECTIVES

At the outset the aims were stated as follows:

To improve knowledge of battery electromagnetic meters, within the UK Water Industry context, re: -

- (a) Generic battery electromagnetic meter performance and uncertainties
- (b) Practical installation effects on full bore meters, (battery v mains)
- (c) Calibration and traceability, for both full bore and insertion probe meters
- (d) Application of electromagnetic insertion probes for in situ meter verification and implications for linked water balance calculations

Therefore, first reconsider the application areas for the technology – the “where” – and then the associated “how good” aspects.

8.1.1 Scope of the regulatory inputs

Regulatory Flow Measurement Input	Type of Flow Meter			
	Mains Emag	Battery Emag	Insertion Mag	Inference meter
Abstraction metering	X	X	X	
Water into supply	X	X	X	
Baseline consumption	X	X		
Leakage Determination	X	X	X	X

Table 8.1: Regulatory issues regarding application suitability

Regulatory Data Quality & Traceability focus	Type of Flow Meter			
	Mains Emag	Battery Emag	Insertion Mag	Inference meter
Active Verification			X	
Meter Calibration		X	X	
Meter Performance		X	X	
Meter Stability over time		X	X	
Static Verification	X	X		
Process Methodology			X	X

Table 8.2: Regulatory issues regarding data quality and traceability

Table 8.1 above illustrates the application areas for the electromagnetic meter variants relevant to regulatory input plus a category termed “inference”, which can be defined as one where the generated value has been arrived at by indirect calculation involving measured and unmeasured quantities. For battery powered electromagnetic meters, one can see that measurements cover all areas whilst the focus on quality is dependent upon

the physical deployment. Those areas are illustrated again in figure 8.1, which has been taken from chapter 2.

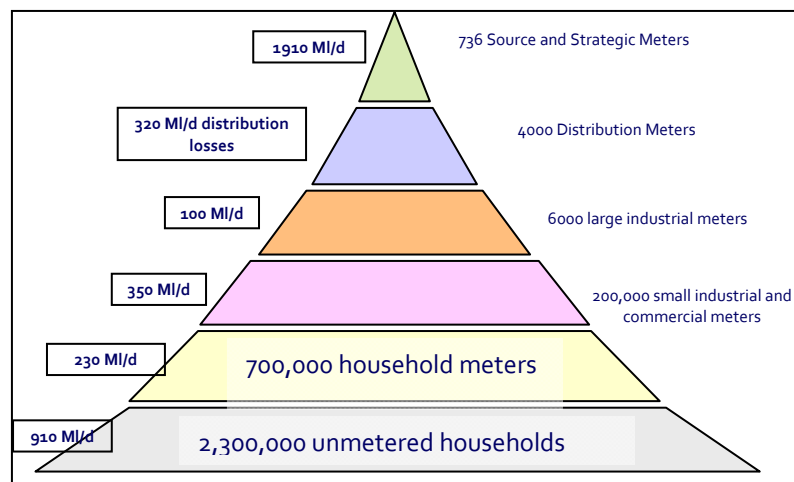


Figure 8.1: Supply system meters and volumes[23]

Linked to tables 8.1 and 8.2, the largest meter volumes and hence greatest sensitivity to accuracy or more exactly to the associated uncertainty of metering, are for the insertion meter. The full bore battery EFM, however, has equal standing because of its use in distribution, industrial and data monitor applications.

8.1.2 Technical, process and quality requirements for regulation

Working to the demands of the annual review of water companies, the water industry regulatory authorities, OFWAT and EA, have the fundamental requirement to gather comparable data from all meters, irrespective of technology. By populating tables 10, 10B(i) and table D, as set out in appendix 1, 2 and 3, OFWAT is able to derive individual water balances which include the value of leakage, expressed as a percentage of the distribution input.

The data, as described in chapter 2, is banded according to confidence grades and reliability grades are allotted for the water balance. Fundamentally, to assure the data, taken from whichever meter technology or inferred source, shall require:

The collection of traceable evidence

– which is

Accurately collected

– by competent, trained personnel using

Independently calibrated equipment

– to create a

Verification record database

– which can be

Objectively analysed

– and

Categorised using uncertainty techniques

– and

Securely archived

- to achieve a single
- Metering installation uncertainty**
- which can be subject to
- Periodic, independent review.**

Each of these aspects will be considered in the light of the work which has been undertaken. However, the relative importance of each aspect is dictated by the nature of the individual water balance. To understand this, an example balance was constructed to exercise the mathematical Maximum Livelihood Evaluation (MLE) balancing mechanism.

8.2 AN EXAMPLE OF THE IMPORTANCE OF WATER BALANCE METERING PERFORMANCE

Figure 8.2 illustrates elements contributing to unaccounted for water losses (UFW). The diagram provides a flavour of the very different ways in which the basic definition of a water balance, namely total water delivered (TWD) = total customer use (TCU), can be imbalanced from the failure or the inability to account for differing uses of water.

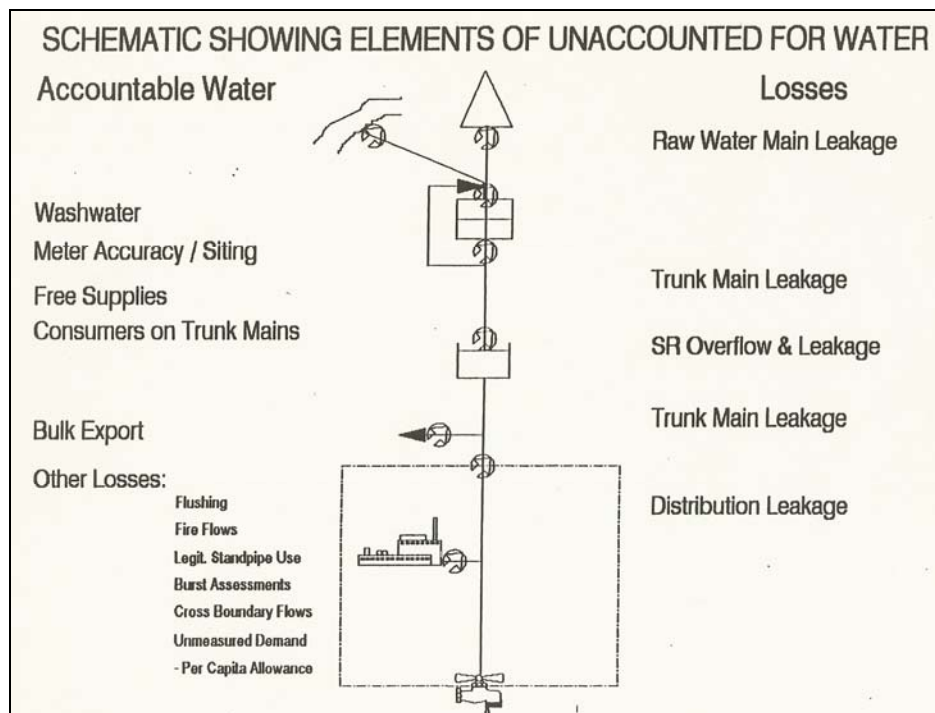


Figure 8.2: Generic water balance: elements of unaccounted for water (UFW)[91]

This overview may be developed to show the components of TWD, often equivalently termed water into supply (WIS). The illustration in figure 8.3 is courtesy of Yorkshire Water and relates to 1991.

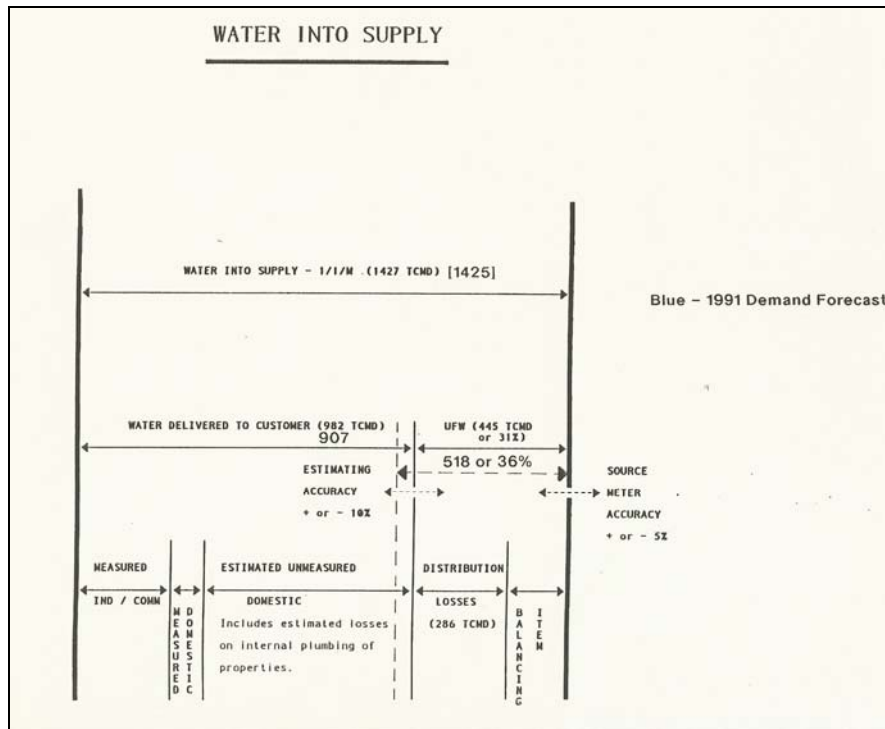


Figure 8.3: Breakdown of total water delivered or water into supply

Shown on the diagram are Yorkshire Water's estimated uncertainties for their source meters, $\pm 5\%$, and for the water delivered to customers, $\pm 10\%$. Finally, in figure 8.4, one can observe the component parts which make up the UFW, which for YW stood at 31% of TWD but which was forecast to increase to 36%; some 445 TCMD.

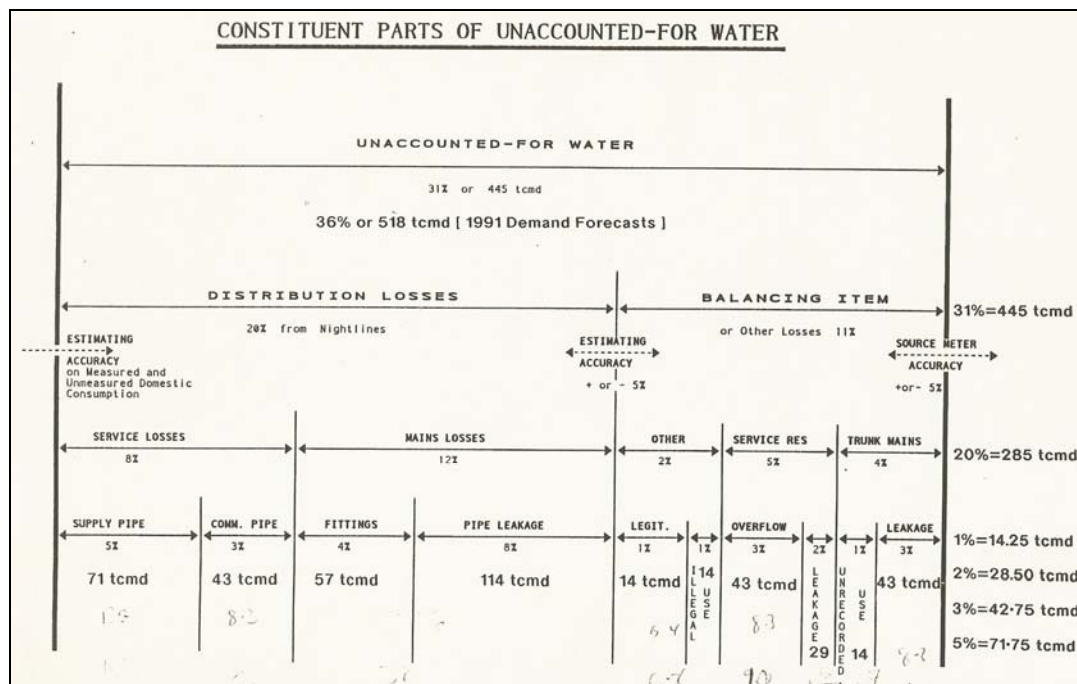


Figure 8.4: Component parts of Unaccounted-For Water (UFW)

8.2.1 Sensitivity to metering quality in calculating the water balance

In understanding the calculation of a water balance, both the water components and their associated uncertainties will comprise a mixture of both inputs and calculated quantities. The nature of the way in which such a water balance is presented is therefore very important and is prescribed by OFWAT.

Thus, in the OFWAT June Return Table 10, the balance is essentially fixed to a zero value, as if the components were invariant quantities. So, although undoubtedly useful for summary accounting and political purposes, this form of presentation is immediately at odds with the knowledge that the contributing components are all subject to uncertainty. Fortunately, this is recognised elsewhere in Table 10 of the June Return, which allows confidence grades to be specified for many of the components.

Inevitably, in such a situation, the best that one is going to be able to do is to construct an approximate confidence interval for a particular calculated balance value. For example, one might state that “the interval -18Ml/d to +27Ml/d covers the TRUE balance value with confidence of 95%”. The difficulty in grasping this concept may be lessened by examining the diagram below, figure 8.5.

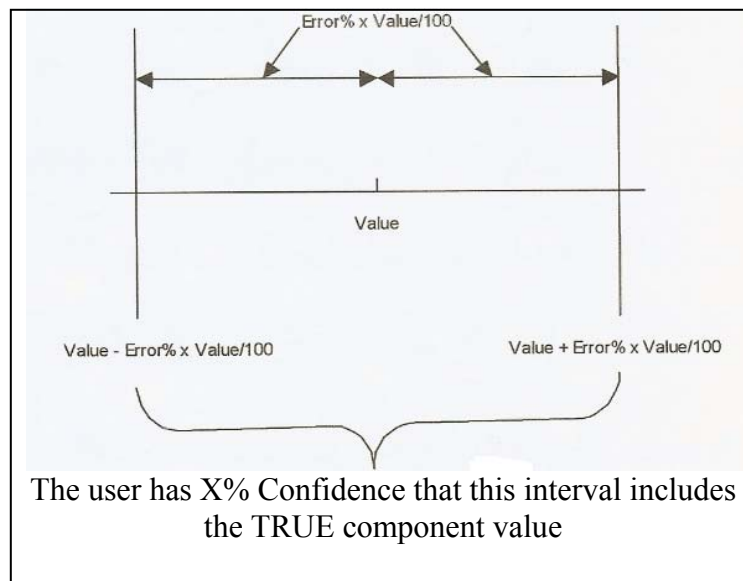


Figure 8.5: Illustration of method of defining confidence allied to an interval

In the figure, the user states that he has X% confidence that the interval, which is bounded by $\frac{(InputComponentValue - Uncertainty\% * ComponentValue)}{100}$ at the lower end and $\frac{(InputComponentValue + Uncertainty\% * ComponentValue)}{100}$ at the higher end.

An example would be where the user states an input value to be = 100%; the uncertainty as 5%; and X% as his confidence =95%. The user is then stating that the TRUE value of the component, which of course he does not know precisely, lies in the interval between 95 and 105.

8.2.2 Illustration of water balance sensitivity

In understanding the calculation of a water balance, both the water components and their associated uncertainties will comprise a mixture of both inputs and calculated quantities. The nature of the way in which such a water balance is presented is therefore very important and is prescribed by OFWAT [26].

Thus, in the OFWAT June return Table 10, the balance is mathematically fixed to zero, as if the components are invariant quantities. Whilst this artifice is useful for summary accounting and political purposes, the form of presentation is at odds with the knowledge that each of the contributory components is subject to uncertainty. This uncertainty is therefore recognised elsewhere in Table 10, where the use of confidence grades, linked to the individual input components, provides the basis for allocating the range of values within which the true measurement lies. Once these values have been defined OFWAT require that the data be mathematically rearranged to deliver a zero sum balance between the component inputs and outputs.

As a means of demonstrating the impact which changing metering performance may alter the overall water balance calculations, a spreadsheet was constructed, using as its basis the guidance provided in the UKWIR 1999 report which analyses water balance errors [92]. This report implements the prescribed OFWAT method described in the June Return Reporting Requirements and Definitions Manual [26].

Data for the demonstration water balance model was taken from the NEL paper by Sattary et al. concerning the UK water company AWS. The utility of choosing these data is that Sattary [93] makes reference to the meter verification uncertainties that are relevant to the present work.

Consider the model which is shown in figure 8.6. In this model, the user is able to assign two values to each of the individual water supply or water use components. The first is the estimated volume flowrate, in megalitres a day and the second the known or estimated uncertainty associated with that particular component or measurement. As can be observed, the input values do not, unless pre-organised, lead to a natural balance of the relationship between TWD and TCU.

In the UKWIR per capita consumption methodology [87], the use of variance, proportional to the square of the confidence interval, is advocated as a means of distributing the errors to arrive at the zero sum balance. However, no formal justification for this approach is given in the report. The calculations undertaken therefore followed extant water industry practice but are not rigorously underpinned in theory.

The use of a maximum likelihood estimation (MLE) methodology is employed in the UKWIR approach, the underlying mathematics of which are set out in Appendix 16. As illustrated, the MLE methodology adjusts each component to balance the TWD and TCU components. The question which must then be posed, against the background of balancing the system, is which elements in the particular arrangement are most sensitive to measurement performance, which in turn relates to the meter measurement type e.g. EFM, Woltmann; turbine, insertion probe etc.

	Component of flow (ML/day)		Component uncertainty U %		Value of Component U (ML/day)	Component of flow post "MLE" adjustment
Water Delivered						
Treatment works output	1,203.80	+/-	5.00	+/-	60.19	1,215.17
Water imported	1.20	+/-	5.00	+/-	0.06	1.20
Total water into supply=	1,205.00	+/-	5.00	+/-	60.19	1,216.37
Water exported	68.80	+/-	3.00	+/-	2.06	68.79
Distribution Input =	1,136.20	+/-	5.30	+/-	60.23	1,147.59
Distribution Systems operational use	13.50	+/-	25.00	+/-	3.38	13.46
Legally unbilled water consumption	12.30	+/-	25.00	+/-	3.08	12.27
Illegally unbilled consumption	2.40	+/-	25.00	+/-	0.60	2.40
Distribution Losses	158.50	+/-	10.00	+/-	15.85	157.71
Unmeasured Supply Pipe Leakage	51.10	+/-	25.00	+/-	12.78	50.59
Total undelivered =	237.80	+/-	8.78	+/-	20.87	236.43
Total Water Delivered =	898.40	+/-	7.09	+/-	63.74	911.16
Customer Use						
Domestic billed Measured	149.00	+/-	5.00	+/-	7.45	148.83
Industrial billed measured	99.20	+/-	5.00	+/-	4.96	99.12
Commercial billed measured	168.90	+/-	10.00	+/-	16.89	168.00
Total billed measured =	417.10	+/-	4.58	+/-	19.11	415.95
Meter under-registration	12.50	+/-	20.00	+/-	2.50	12.48
Measured Supply Pipe Leakage refunds	3.90	+/-	25.00	+/-	0.98	3.90
Legally used hydrants	1.00	+/-	25.00	+/-	0.25	1.00
Domestic internal Supply Pipe Leakage	1.20	+/-	50.00	+/-	0.60	1.20
Total adjustments =	18.60	+/-	14.84	+/-	2.76	18.58
Total measured =	435.70	+/-	4.43	+/-	19.31	434.53
Unmeasured Per Capita Consumption (l/person/day)	139.94	+/-	5.00	+/-	7.00	139.46
Number of persons	3,110,000.00	+/-	5.00	+/-	155,500.00	3,099,354.19
Unmeasured domestic	435.21	+/-	7.07	+/-	30.78	432.24
Unmeasured non-domestic	7.20	+/-	10.00	+/-	0.72	7.20
Total unmeasured =	442.41	+/-	6.96	+/-	30.79	439.44
Specific demand from defined major Customer	36.10	+/-	5.00	+/-	1.81	36.09
Meter under-registration of major Customer	1.10	+/-	20.00	+/-	0.22	1.10
Total for major Customer =	37.20	+/-	4.89	+/-	1.82	37.19
Overall total for Customer Use =	915.31	+/-	3.98	+/-	36.39	911.16
Water Balance						
[Total Water Delivered – Total Customer Use] =	-16.91	+/-	433.95	+/-	73.40	0.00
The TRUE Balance is in the Interval	-90.31	to	56.48		ML/day	
Components "adjusted" to give "zero" balance						
Adjusted water balance using the MLE maximum likelihood estimation methodology reference [26, 87]						

Figure 8.6: Example of generic water balance employing an MLE methodology to regulatory requirements

Model sensitivity results

Prior to changing component values, the TRUE water balance can be seen to be -16.91 Ml/d, i.e. the customers are taking more water than is being supplied!! However, the uncertainty in this figure is $\pm 434\%$, such that the interval, within which the balance of -16.91 may be claimed to lie with 95% confidence, is from -90.31 Ml/d to +56.48 Ml/d, i.e. the balance may be stated as -16.91 ± 73.40 Ml/d. Hence, by deriving the interval information one automatically places the balance in context, as opposed to merely presenting the arithmetic result unqualified.

Consider now a series of alterations to the uncertainty of the components and the effect which this has on the water balance. The sequence is as follows:

- (a) Baseline run with values as estimated by AWS
- (b) Works output and water imported revised to 2% (from 5%)
- (c) Distribution losses and unmeasured supply pipe leakage revised to 2%
- (d) Industrial and commercial revised to 2%

The results are shown in table 8.3 below.

TWD-TCU	Difference in Mld +/-	Difference less Total UCV	30.78 = Total UCV (Unmeasured Customer Volume)			
-16.91	73.40	42.62	Baseline Case: see Note below			
-16.91	48.41	17.63	Works Output & Water Imported set at 2% not 5%;			
-16.91	44.05	13.27	Distrib losses & unmeasured SPL at 2%			
-16.91	40.57	9.79	Industrial & Commercial at 2%			
Interval in which the TRUE value for the Water Balance of						
-16.91 Mld lies is						
From		To				
-57.48 Mld		23.66 Mld	equivalent to an error of +/-240%			
Note:	Baseline Case: 95% Confidence that +/-5% uncertainty will mean that the TRUE component value lies within the interval					

Table 8.3: Illustration of sensitivity in water balance to input component

The table shows the balance of TWD-TCU, the associated error in that number, plus the error less the total unmeasured customer volume (UCV). The latter remains essentially static throughout the exercise and so it is easier to see the impact of the changes by examining the data in the column showing (Difference-TCU).

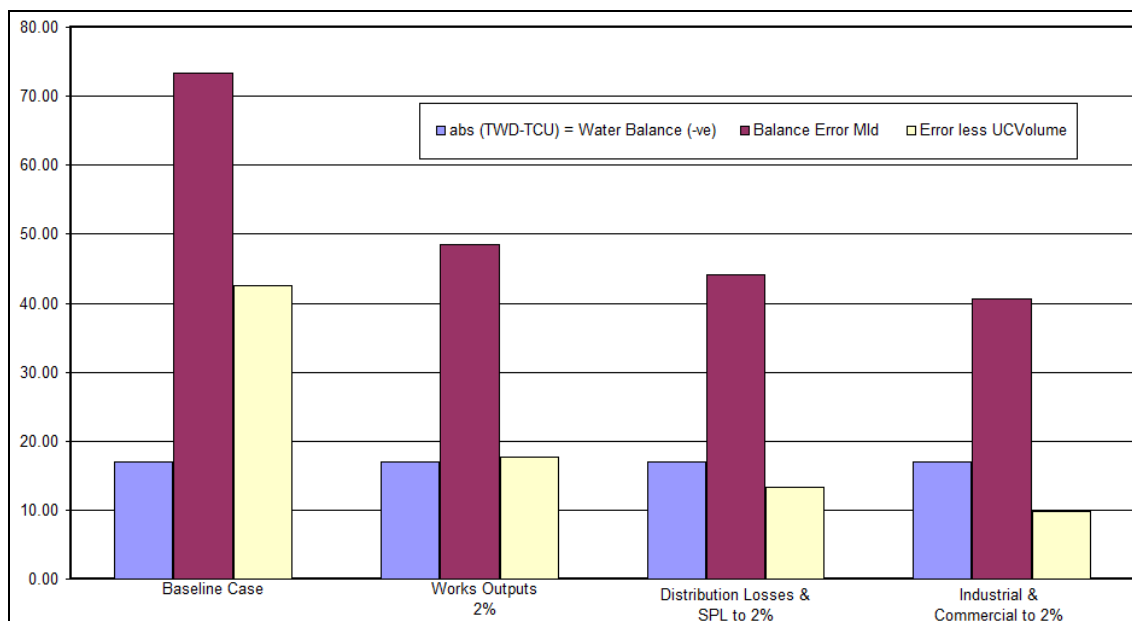


Figure 8.7: Plot of changes to water balance as input component accuracies change

The impact on the water balance as the input component accuracies change can be seen clearly. By reducing the errors associated with the major components comprising both sides of the water balance, a significant reduction, not in the balance figure, but in the error interval which may be legitimately ascribed to the overall balance, is achieved. For the particular example based on measurements from Anglian Water Services, the uncertainty reduces from $\pm 434\%$ to $\pm 240\%$.

8.2.3 Positioning of battery electromagnetic instruments in the water balance

In regard to the above example, the importance of battery meters to water balance measurements lies in their deployment in the precise areas which have been shown by the example to have greatest impact on the calculated balance errors. Namely, those at the top of the chain, supply and import meters, plus those applicable to quantifying distribution, supply pipe leakage – via SAM's etc – and in recent years, the measurement of both industrial and commercial meters, where the enhanced performance can deliver improved precision for the volumes taken.

8.3 IMPACT SUMMARIES FROM THE INDIVIDUAL RESEARCH AREAS

8.3.1 Impact from full bore meter performance evaluation

The battery technology met published ISO standard performance limits, not only in the advised 10D/5D, upstream/downstream configuration but when operated under non-ideal conditions and close to a PRV. As such, the input uncertainties for water balance (WB) calculations may be confidently and irrespectively set to the ISO MPE's. However, the diurnal nature of a particular meter's flow profile will still determine the actual figure which should be quoted to OFWAT when referenced to a named source or aggregated WB component. This is no different to normal.

When operated in the Cranfield laboratory, excitation was not an issue due to the long periods over which volumes were aggregated. Nevertheless, the issue of scatter and

sensor noise becomes important at very low flows and especially during calibration, or when measuring at very low flows, such as in the SAM application. As such it is important in completing the understanding of battery electromagnetic meter performance and limitations.

The reduced area flowtube design which was tested, contributed in a positive manner to the ISO compliant performance, which included meeting a limiting pressure drop requirement. Therefore as with MPE, there are no regulatory or practical issues.

8.3.2 Impact from battery probe calibration, uncertainty and traceability

Present practices with battery insertion probes vary widely across different water companies, often because of the use of contractors who operate according to internal not external specifications. The practical and potential policy advances brought about by the de-facto probe calibration standard, developed during the course of the work, are that the uncertainty spread in data submitted to OFWAT could be reduced.

The illumination of the probe characteristic, varying as it does with Re and velocity, offers the opportunity to quantify a total uncertainty for a particular site application.

Generically, the past uncertainty assessment undertaken by Sanderson and Thomas in 1996[94] remain to be updated and released as a working standard. The present work supports such a future development but will not presently impact on the data being returned to OFWAT or the EA.

The finding of calibration dependence on probe tip condition is of great importance and has strong impact but, without implementation of formal re-calibration periods for insertion probes, coupled with use of a traceable probe calibration standard(s), there is no mechanism to flag increased variability in the returned data to OFWAT and EA.

The ability to confidently use ex-factory probe calibrations has been shown to be limited but without a formal probe calibration standard, the uncertainties presently ascribed should be regarded as optimistic and await the updating of a generic statement, as referenced earlier. It is the view of the probe manufacturer that the present factory calibrations are adequate for the needs of the market.

8.3.3 Impact from specialist profiling software

As a result of discussions with the EA, it was made clear that the quality of verification data generated from insertion techniques varied so widely that comparative assessments were rendered worthless. Therefore, the impact of the developed specialist software is potentially significant to the regulator(s) because of its ability to remove errors resulting from both unstructured application methods and operator error whilst delivering an objective and complete record of the profiling/verification work undertaken.

The quality impact is therefore substantial and is amplified by the de-facto creation of a standard data archive for verification data plus the associated information such as who did the work, when, where, at what time etc. Such archive material allows the regulator to recalculate datasets, a utility which in light of the findings concerning probe tip condition and calibration shifts has substantial economic and WB implications.

At present, a definitive answer to the question of what is a “good” site and what is a “bad” site, in respect of a velocity profile, has not been reached. The ability of the specialist profiling package to visualise, both to the operator at the time of test and subsequently to the regulator, the full time series data which has been collected, moves part-way to realising this ambition and is useful in the practical and regulatory sense because of the standardised format. The question of categorisation, nevertheless, remains.

8.3.4 Impact from establishing probe baseline performance

This work demonstrated the stability of the de-facto, laboratory insertion probe standard. In addition an uncertainty of between 1.1 and 1.4% for the laboratory standard’s profile factor was arrived at. However, this did not in itself have a direct regulatory impact.

Likewise, the examination of varying the values of ‘m’ and k on the profile factor generated knowledge of a useful and practical nature but which has no direct regulatory impact.

The usefulness of these two pieces of work should therefore be seen not in relation to direct regulatory impacts but in building knowledge concerning the nature of profile and velocity data under essentially ideal conditions. In turn this has created for the first time an objective, evidence based database of results describing the quality as well as the traceability of probe profiles.

Use of the profile factor, F_p , as a stand alone value to fully describe pipe flow conditions was shown to be inadequate if lacking a suitable supporting statistical description, NSE. The use of NSE expressed either in absolute form or when presented as a ratio to its value on the pipe centre line, proved to be a moderately useful indicator of the hydraulic conditions. Thus, when used in conjunction with F_p the use of NSE provided a better description of the measurement environment than F_p alone.

One key finding, relevant to the regulator and useful in avoiding misleading statistical descriptions of profile state, was that expanded uncertainty and variable expanded uncertainty were highly dependent upon the probe transmitter parameter set-up - because of internal filtering of the sensed signal. From a regulatory impact, this translates to a requirement that individual probe set-up parameters are collected or standardised. Without this, it is possible to generate widely different performance and statistics for the same location and be quite unable to trace the cause of the difference.

8.3.5 Impact from Probe tests at manufacturer

At the beginning of the work twenty ex-factory probes were tested on the Hams Hall 260mm reference section and found to be almost 5% in error. Ultimately, the bulk of the discrepancy was assigned to the factory profile factor which had been set from theoretical considerations, i.e. not measured. This remains the case as far as is known and differences ranging between 3% and 5% still existed in 2004.

The regulatory impact of these differences is open to interpretation but, because of the lack of a traceable reference underpinning the manufacturer's calibrations, combined with limited flow ranges, it could – controversially - be argued that at present the ex-factory probe calibrations are inadequate for the application area.

Regarding the tests on the 1200mm pipe, the severe vibration encountered and subsequent recalculation of the advised maximum insertion lengths impact on the validity of probe based verifications undertaken on pipework with flows close to the published limits. The impact on the regulatory data, should, at present, be to flag results for attention where the published insertion/velocity limits have been approached.

8.3.6 Impact from probe field trials

The major finding from field trialling of the probe and the AutoProfile software was that battery powering, at the manufacturer's standard excitation frequency, will lead to significant and unacceptable errors when profiling. From the regulatory viewpoint it is therefore necessary to know the set-up of the instrument at the time of measurement. Note that when reprogrammed, the same probe was capable of functioning adequately.

Use of the AutoProfile software generated more evidence that a statistical description of a site's velocity profile is as important as the headline Fp result and reinforces the case for development of a minimum requirements document encompassing all aspects which relate to both site and probe accuracy/traceability.

Important practical evidence was collected showing that profile reproducibility can be measured to better than 1% in the field. Thus, although normalisation of profile data may be desirable at many sites, it is by no means a necessary condition.

Answering the question which is a "good" site and which is "bad" still remains. However, the simpler case for standardising the data collected, the site details and the equipment information and placing in one file, such that a single repository can cover a particular verification measurement, is compelling.

In terms of confidence, aggregation of annual meter verification results, including the profile, are essential in view of the variability seen in probes returned for re-calibration. As is the requirement to be able to hold details of the equipment, so forming a traceable record year on year of what was used, where, when and by whom.

8.3.7 Impact from the audit of full bore battery meter field performance

The opportunity to audit 100 battery meters after 5 years of being buried generated a series of highly significant findings which translate into Regulatory actions in order to protect confidence in table 10 data.

Specifically, regular verification of battery electromagnetic but also 'regular' electromagnetic meters which have transmitters holding flow sensitive set-up information which is user accessible is essential. The technology has been shown very much not to be 'fit and forget', with all the implications for WB data integrity which this implies.

Excitation mode is key to correct battery electromagnetic operation and may require modification if ageing of components induces long term drift; as was evidenced by the SAM audit experiments using 1second excitation in contrast to the standard 15second refresh period.

The key to benchmarking performance is thereby to ensure data integrity by regularly examining the electronic configuration, including all relevant meter software, firmware and hardware parameters. Only in this way can regulatory sensitive information be assured. A key regulatory feedback concerning battery EFM meters is therefore that stability cannot be assumed, it must be defined and measured by way of regular verification.

Recalibration of one of the ex service battery EFM meters exposed a second regulatory impact specific to the battery meters audited, namely that the original factory calibration was flawed, failing to encompass very low flows. Per-se, verification procedures cannot identify this as a problem. For this reason it is a critical issue which demands either formal regulatory calibration requirements to be put in place or amendments to be made to the ISO/CEN standards such that the factory procedures assure users of the validity of the calibration/meter performance.

8.4 DELIVERY OF ORIGINAL OBJECTIVES

At the beginning of the work the intent was to improve the performance, calibration, limitations, verification and quality of flow data obtained from battery electromagnetic meters, in order to increase confidence in the technology and allow better regulatory scrutiny and interpretation of field results. This in turn would lead to improvements in respect of the calculation of the water balance, metering policy and decision making.

At the end of the work one may summarise the detail of the regulatory impacts given earlier, by categorising them and overlaying on the generic tables describing the scope of the regulatory inputs, which refer to application suitability and to data quality and traceability.

Thus, by colour coding individual impacts into four self explanatory categories:

No Major Issue(s)		
Minor Issue(s)/ Acceptable		
Minor Issue(s)/ Attention Requ'd		
Major Issue(s)		

The generic tables can re-interpreted as shown:

Regulatory Flow Measurement Input	Type of Flow Meter			
	Mains EFM	Battery EFM	Insertion EFM	Inference meter
Abstraction metering				
Water into supply				
Baseline consumption				
Leakage Determination				

Table 8.4: Regulatory issues regarding application suitability

And:

Regulatory Data Quality & Traceability focus	Type of Flow Meter			
	Mains EFM	Battery EFM	Insertion EFM	Inference meter
Active Verification				
Meter Calibration				
Meter Performance				
Meter Stability over time				
Process Methodology				

Table 8.5: Regulatory issues regarding data quality and traceability

From the above summary tables it can be concluded that battery electromagnetic meters require careful consideration by the regulatory authorities in all of the key areas concerning data quality and traceability.

9. MAJOR FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

9.1 MAJOR FINDINGS

The primary aim of the research presented in this thesis has been to address the performance, calibration, verification and limitations of the battery powered electromagnetic (EFM) meter. Major findings deriving from the individual investigations are now presented, followed by conclusions and recommendations for further work.

FULL BORE BATTERY EFM CALIBRATION AND PERFORMANCE

1. The laboratory tests validated under ideal hydraulic conditions, for both battery and mains operating modes, the EFM manufacturer's specified MPE performance claims; subject to the limited number of points tested. These manufacturer MPE limits are more demanding than those specified in ISO 4064.
2. The EFM remained compliant with the ISO MPE limits when subject to severely distorted hydraulic conditions: generated either by installing the meter in a standardised bypass arrangement with rotated pipework, or by operating in close proximity to a gate valve or a pressure reducing valve (PRV).
3. Compliance with the more demanding manufacturer specified MPE limits was not achieved when the EFM was operated in proximity to a gate valve or PRV.
4. Spacing the EFM away from either the PRV or gate valve does not improve performance significantly and compliance with the ISO MPE limits may be achieved without spacing. A similar finding applied to the mechanical Woltmann meter tested.
5. The finding, subject to the number of points tested, that it is possible to bolt the EFM directly to a gate valve or PRV and retain ISO 4064 MPE compliance has major practical and economic implications. This is (a) because it will allow installers to be more flexible when installing a meter in existing pipework; (b) because it will reduce the pipework component requirements for any given installation; (c) because size of the installation and therefore the cost, will be reduced.
6. Digital data acquisition, built around an RS232 serial port logging technique, proved valuable in minimising recording and transcription errors. However, the implementation adopted using two separate PC's to collect the data from the EFM and the master meter, proved very time consuming and cumbersome to analyse. It was therefore concluded from the Cranfield laboratory work that to realise the potential of the digital recording approach an improved data collection method was required, built around the transfer of data from the meter serial port.
7. The spread in meter results, observed when repeating EFM tests under the same conditions, highlighted the practicality of using MPE limits as a method of specifying the performance of the low power battery EFM design. However, the

number of points tested was limited throughout the test programme, restricting the confidence with which the measured MPE compliance may be generalised.

8. Similarly, the MPE approach proved equally useful in accommodating the characteristic of the mechanical Woltmann meter test results.

BATTERY INSERTION PROBE CALIBRATION AND PERFORMANCE

The objective of the battery EFM probe work at the Hams Hall flow laboratory was (a) to improve knowledge of the probe's generic calibration, performance and limitations and (b) to benchmark the level of performance achievable when using a battery probe for meter profiling/verification purposes. All of the individual testing targets were achieved, with specific results as follows:

1. Use of a beam-pitot based method enabled the velocity profile for a reference section of 260mm pipework to be derived with an uncertainty of 1.4%, or, should the profile be measured using a battery electromagnetic probe, 1.1%.
2. An independent, traceable, probe calibration standard was created through the use of the above reference section and the use of specialist digital data recording software, developed to interface between the UKAS calibrated master meter and the particular probe under test.
3. By combining digital rather than pulse derived data with a second piece of specialist software, the technical description of the master meter calibration was improved by a factor of two; with the random uncertainty component reducing by 3.5:1 to 4:1 across the flow range.
4. Use of the developed calibration facility allowed the detailed shape of individual probe calibration characteristics to be measured, as well as quantifying performance limits. Both the characteristic and performance limits were found to vary widely between probes. Representative uncertainty figures for the meter factors of probes demonstrating satisfactory measuring performance, show a spread of between 0.8% and 2.8%.
5. The physical state of the insertion probe tip, including its surface condition, was discovered to be a major determinant in calibration performance. Localised damage in the shape of vertical scratches or abraded bottom tip edges caused significant changes to the probe characteristic impacting on valid use as a profiling/verification instrument.
These findings are important to the quality and accuracy of regulatory meter verification data, because they are typically obtained over periods of time which are sufficiently long for there to be a likelihood of probe damage occurring.
6. Recalibration of 10 probes, following their use after a year in service verifying strategic WISPY meters, found substantial changes to the calibration factors, reproducibility and stability. Of the 10 probes tested only half showed performance which was deemed acceptable; namely a meter factor within +/-2% of the previous year's value and an uncertainty over the calibrated flow range of better than +/-5%.

7. Work in the laboratory measured the performance of a battery insertion EFM probe when mis-aligned by up to 15 degrees; with respect to the direction of the pipework in which it was installed. The conclusion reached, in contrast to that for the mechanical insertion probe turbine designs cited by Miller [70], is that the influence of misalignment on battery EFM probe output is much smaller. For practical situations, where misalignment of 1 or 2 degrees is representative, the spread of errors due to misalignment lies in a band below 0.5%.
8. An unexpected but important limitation to the application of battery probes, highlighted as a result of the misalignment testing, is that it is important to avoid sharp rotation when initially aligning a probe. Failure to do so may result in the measured velocity being offset in the short term by up to 1.5%.
9. By using specialist software to combine the normally separate profiling and meter verification functions, the performance of the battery EFM probe as a meter verification tool was accurately benchmarked; as installed under the Hams Hall standard laboratory conditions.
10. The result of the benchmarking exercise was to demonstrate a -1.1% difference between the insertion probe and the meter-under-test, which was UKAS calibrated with an uncertainty of 0.12%. Overall, the uncertainty of the probe based meter verification was assessed at +/-1.6%.

The work thus demonstrated that an overall performance of better than 2.0%, with an attendant uncertainty of +/-2%, is achievable when using a battery EFM insertion probe as a meter profiling/verification tool.

PROBE VELOCITY PROFILING AND METER VERIFICATION

The conclusions regarding velocity profiling and meter verification are given, grouped against the appropriate work area.

Data collection and development of a profiling/verification software tool

1. The development of a software based velocity profiling tool enabled the collection of high quality data, both in the laboratory and field environments. This data was used to improve the knowledge of probe performance and to characterise the profiles at differing locations.
2. The process driven design philosophy pursued for the profiling software enabled delivery of consistent results, irrespective of individual operator. Such design is fundamental to establishing a consistent verification methodology across differing sites and companies. In line with EA requirements it demonstrated in the field the repeatable, objective data collection necessary to administer the verification of WISPY meters as undertaken by the regulatory authorities.
3. As part of the profiling software a series of performance indicators were developed. These allowed qualitative assessment of the profile measurements. Baseline values were established both at Hams Hall and at the manufacturer's plant and used to benchmark field test data quality.

4. Limitations, normally applying to the insertion battery probe technique, are mitigated through the provision of real-time visual communication and feedback on the progress of the pipe velocity profile to the operator.
5. Flow, or other hydraulic changes which occur over the time of the profile and which may distort the quality of the data are able to be observed and acted upon. Additionally, the requirement, inbuilt to the software, to repeat three key profile points allows assessment of the reproducibility of measurement and underpins the quality of the complete profile.

Baseline velocity profile performance

1. A series of repeat profile determinations, spread over 12 weeks and using different probes, established through the use of the profiling software that the Hams Hall laboratory profile can be generated, regenerated and reliably determined over time to better than $\pm 1.0\%$ at a similar flow and better than ± 2 per cent when the repeat flow range is extended.
2. However, adoption of the manufacturer's published probe insertion factor, "K", as part of the profiling software algorithm, was shown to result in skewing of the measured profile from true. Systematic variation of "K" and "m", the Von Karman coefficient linked to near pipe-wall profile effects, were therefore simulated over a wide range of practical values using the developed profiling software. Their combined effects were shown to alter the velocity profile calculation result by between -0.7% and $+0.4\%$.
3. Varied singly, "K" was found to strongly affect the calculated positions of the mean velocity points on a given profile. As the manufacturer changes the value of "K" with pipe size this sensitivity indicates that use of the calculated mean positions could lead to substantial errors in deduced flow.
4. The evidence from use of the profiling software on the manufacturer's calibration line indicates that when active pump control is implemented and combined with smaller pipework, hydraulic flow stability improves considerably. Point velocity reproducibility becomes better than 0.4% , the NSE statistic for flowrate is halved and the other statistical descriptors are generally improved.
5. Referring to the manufacturer's 212mm probe calibration pipework, the absolute value of F_p measured by the profiling software was 0.827. This is -2.7% lower than the textbook value used by the factory for their pipework profile factor when calibrating probes. It contrasts with the -0.6% difference between the beam pitot derived F_p and the insertion probe F_p at Hams Hall, measured using the same software.

Field trial outcomes

1. The field trials illuminated a significant source of error should a battery EFM probe be operated in its ex-factory, 15 second excitation frequency mode when

profiling. Failure to reprogram a transmitter to 1second excitation frequency was shown to result in gross errors in the profile determination.

2. Both the site and the laboratory work confirmed the need to be able to record individual, raw, point-velocity data samples in order to be able to adequately assess profile quality.
3. Repeatability of a particular profile must be demonstrated if an operator is to be able to claim to characterise the uncertainty of a meter verification using the probe methodology.
4. Visualisation, on site and in real time, of the measured point velocities fundamentally changes the operator's ability to control the verification process and hence to delivery qualified, quality, profile/verification results.
5. Statistical descriptors, whilst needed to quantify the flow data for individual site records, should be interpreted only in conjunction with the visual record. The two approaches are complementary.
6. The profiling software provides traceability of all field acquired data for later analysis and independent scrutiny by the regulator. It delivers qualified, quality field data capable of matching that from the laboratory testing. This complements the rigour applied to the calibration of the battery insertion meter itself and increases the overall level of confidence in verification results obtained using a battery EFM probe based technique.
7. Field probe performance, using the developed software, was able to demonstrate, on a number of sites, that profile reproducibility can better $\pm 2\%$, although data noise and stability are degraded from that seen in the laboratory. For sites where the flow is pumped the achievable profile reproducibility can be better than $\pm 0.5\%$.

Probe vibration limits

1. Re-examination of the present insertion probe velocity limits indicates that the current published values underestimate the susceptibility of the probe assembly to become mechanically excited and enter into sustained vibration. Profiling of the 1200mm calibration line at the probe manufacturer evidenced this view.
2. On the basis of available data and in order to maintain both data quality and safe operation, substantially lower limits than those currently published by the manufacturer for maximum velocity and insertion depth are required. Revised limits have been calculated and are advised to be used with a confidence factor of 10%, chosen on the basis of tests to date.
3. Generation of the range of probe velocity limits has shown that vibration induced errors are far more likely to occur under typical water company supply system flows than previously thought. The literature contains no references to this source of error, yet the modelling and measurements indicate that it may be

of significant importance, capable of strongly distorting profile results. This has been observed when measured using the developed software.

4. In order to avoid significant errors occurring in the regulatory data record all future meter verification data, obtained using insertion and profiling methods, should be carefully scrutinised for compliance with the revised vibration and velocity limits.
5. In order to refine the limits and confidence factor presently derived, an alternative to the simple modelling method used in this thesis should be developed using modern computing power allied to modal analysis.

MEDIUM TERM PERFORMANCE OF BURIED BATTERY EFM METERS

The objectives set at the start of the audit work examining the buried SAM meters were threefold, namely: (a) to assess the quality of battery EFM data after 5 years of operation; (b) to check the calibration stability of the technology and (c) to examine the ongoing maintenance and verification needs of battery EFM's.

The conclusions are as follows:

1. As a representative example of the performance of battery EFM network metering, Severn Trent Water's SAM was not typical. However, each of the specific SAM problem areas which the audit identified represents a generic influence factor for this type of technology.
2. Because of the spread of the problems affecting individual meters it did not prove possible to quantify, overall, the quality of data. Nevertheless, one can conclude that, in the absence of objective checks on the accuracy of each meter's data, the flow statistics derived for the 96 SAM meters would be assessed under the OFWAT grading scheme as C3 or C4; unreliable, with an assessed accuracy of 5-10%. This is direct contrast to the laboratory performance findings for the battery technology.
3. The recalibration of one of the 96 SAM meters established that the measured flow was inaccurate and failed to conform to the published specification. By exchanging the electronics board in the excavated sensor head it was established that the output of the battery EFM design had not drifted but that the absolute calibration of the sensor, programmed from new, was incorrect. It was this that had led to significant errors in the measurement of low flow data. However, despite this finding the audit found no evidence of long term drift associated with the battery EFM technology.
4. Accurate calibration of battery EFM technology is fundamental to achieving appropriate measurement in the application areas targeted: leakage and low flow revenue. Nevertheless, significant errors in the measurement of low flow data were uncovered as a result of the re-calibration of the excavated 5year old meter. From this single example it was concluded that there was a generic error inherent in the original factory calibration of all battery EFM meters manufactured up to that date. As a direct result the manufacturer's production calibration schedule was changed for this class of meter, providing additional

calibration points to eliminate the existing problem in the transition and near laminar flow zones.

5. By comparing and analysing meter and data records the SAM audit reached the conclusion that subjective, experience-based user assessment of flow measurements can and often does lead to significant data reporting errors; resulting in a loss of confidence in the overall meter records/dataset. Any system of audit/verification must therefore be based on objective technical tests and not on judgements founded on “knowledge” of a particular meter’s expected flows.
6. As a result of the evidence of poor performance collected during the SAM audit it is concluded that in the long term the performance of battery EFM meters can only be assured by adopting timely, rigorous, in situ audit/verification techniques which must be capable of generating time series records ultimately traceable to the original ex-factory meter condition. Implementation of such meter audit/verification will create sufficient, up to date, technical and administrative information. The user can then accurately judge if the metering system, including detailed setup software setting, is operating to specification.
7. In contrast to its mechanical counterpart, the audit showed that the battery EFM meter requires to be viewed as an integral package comprising both software and hardware elements. This has important implications for the audit/verification method(s) which must be capable of recording, over time, the software status of a meter. This includes both the firmware installed by the manufacturer and all of the possible user adjustable parameters which could affect performance.
8. Unlike mechanical network metering alternatives, battery powered EFM meters demand that the provision of audit/verification maintenance be planned over a timescale of 5 to 15 years i.e. linked to the life of the sensor. This strongly contrasts with the existing two to five year consecutive swap-out of Woltmann type insert mechanisms which are actioned to ensure that the performance of the mechanism remains within specification.
9. It is concluded that the cost of funding the difference between the mechanical meter swap-out maintenance model and that of a rolling audit/verification programme for battery EFM meters has direct consequences for regulatory data quality and confidence - as illustrated by the SAM audit.

Unless resources are committed to battery EFM maintenance on a yearly, bi-annual or five yearly basis etc, the level of confidence which can be objectively ascribed to the uncertainty and provenance of the EFM flow data submitted to the regulatory authorities will be limited. Practically, this could mean that one would be unable to assure the OFWAT confidence grading assigned by the water company, thereby nullifying many of the claimed performance advantages of the battery electromagnetic meter technology.

9.2 CONCLUSIONS

The water industry regulatory authorities, OFWAT and EA, have the fundamental requirement to gather comparable data from all meters, irrespective of technology. Regarding battery electromagnetic meters, the work has highlighted several areas which require addressing to ensure that the regulatory process remains even handed.

1. The work undertaken has shown that battery powered electromagnetic meters, which utilise sampled flow measurement techniques, require much improved calibration to avoid significant errors at low flows. This applies to both full bore and insertion type battery meters and should be addressed at the regulatory or ISO Standard level.
2. A field audit of 5 years old buried meters comprising one water company's small area monitor, discovered a significant weakness in the electronics of the original manufacturer's battery design. This led to measurement drift over time and compromised the regulatory data from this particular monitor.
3. Recalibration of a formerly buried, 6-year old, ex-service battery meter showed that the manufacturer's original calibration method was flawed. This had led to significant errors both at medium and at low flows. The error applies to all manufactured battery meters produced to the time of the recalibration exercise.
4. The source of the calibration error identified for the specific meter manufacturer was generic and applies to all battery electromagnetic meters whose designs are focused on the measurement of low flows in water distribution networks. The impact calculated as a result of the calibration error amounts to between 0.5% and 1.5% of the SAM supply volume. In turn this directly determines the per capita residential leakage which would have been reported to the regulatory authorities. This error is therefore significant within the overall water balance estimation for the water company.
5. A traceable and repeatable insertion probe calibration facility has been established and the stability of the test pipework velocity profile demonstrated over a period of 10 years through periodic recalibration.
6. A method of calibrating battery electromagnetic probes has been developed to overcome existing weaknesses and assess probe calibration uncertainty. Significant differences have been found between this and the particular manufacturer's factory calibrations.
7. It has been concluded that the existing ex-factory calibration of the battery insertion probe tested is inadequate for regulatory purposes, due to limitations in the range and detail of the manufacturer's calibration.
8. Generation of the range of insertion probe velocity limits has shown that vibration induced errors are far more likely to occur under typical water company supply system flows than previously thought. The manufacturer's published limits underestimate this source of error and the literature contains few references to this source of error, yet the modelling and measurements undertaken indicate that it may be of significant importance.

9. Application of the sampled technology used by this class of device has been shown to induce large and unacceptable errors when velocity profiling with battery insertion probes.
10. Insertion probes deployed to verify key strategic water into supply meters exhibit significant sensitivity to probe tip condition, as evidenced during recalibration. Recalibrations have demonstrated that probe stability cannot be assumed over a period of 12 months.
11. Meter verification errors, when using insertion probes, result both from a combination of unstructured application methods and incorrect probe calibration, as well as generic factors documented in the literature.
12. Discussions with the EA resulted in the development of a portable, interactive, software application for velocity profiling and meter verification. This application achieved EA compliance, with the design being capable of meeting regulatory requirements for data traceability whilst addressing the identified errors present in current meter verification reporting.
13. Water company practice regarding calculation of uncertainties applied to electromagnetic meters, whether battery or mains powered, requires standardisation in order to ensure that comparable data is made available to the regulators.

10.3 RECOMMENDATIONS FOR FURTHER WORK

1. During the period over which the research was conducted the market in battery powered EFM meters continued to evolve, with new products claiming similar performance to those examined, being launched. However, within the available time and resources these new instruments could not be evaluated. Therefore, the first recommendation is that work should be instigated to evaluate these newer battery meters and to confirm the generic nature of the present findings.
2. Similarly, in order that the regulatory authorities are able to provide guidance and consider enforcing like-for-like rules, work is required to examine static verification instruments (SVI's). Future work should focus on examining the detailed methods of SVI operation and specifically on creating realistic and rigorous uncertainty budgets for the several SVI style devices which have come to market in recent times.
3. It is recommended that an examination is undertaken of the requirements and associated methods for calibrating battery electromagnetic meters from average down to very low velocities; 1.0m/sec to 0.002m/sec. The reasons are:
 - (a) because of problems associated with the use of a single calibration value to cover the transition range from turbulent to non-turbulent conditions;
 - (b) because of the increasing use of battery electromagnetic meters in the water industry which are operating under these precise conditions and

- (c) because of the high importance of the baseline data, measured by these battery meters, which is then submitted for regulatory water balance purposes.
- 4. In order to validly create comparable water balance statements, where differing metering technologies and meter verification methods are now in use, there is a clear requirement to examine the extent to which formalising and standardising meter uncertainty statements may be possible. At present the problem is highlighted where key water company meters utilise data deriving from different verification methods which attract (widely) varying levels of confidence.
- 5. Finally, it is recommended that the present thesis examination pertaining to the acceptable vibration limits for insertion probes should be re-worked and extended using modern computational modelling techniques.

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Appendix 1: OFWAT June Return; Table 10; STW 2007

[illegible]

Figure 2A-1: Non financial measures, Table 10; STW 2007

Appendix 2: OFWAT June Return; Table 10b(I); STW 2007

June Return 2007 Public Domain							
Severn Trent							
Table 10B(i), Non Financial Measures							
Environment agency data - annual average out-turn							
WRZ NAME	B'ham	East Mids	Forest &	Oswestr	Severn	Staffs &	Shrops
BASIC RESOURCES							
Deployable output	329.6	848.49	56.79	21.48	644.12	259.86	
Outage allowance	14.7	35.8	1.8	1.8	27.8	20.5	
Water available for use	314.9	812.69	54.99	19.68	616.32	239.36	
RAW WATER							
Raw water abstracted	318.01	872.98	48.69	16.91	621.39	212.57	
Raw water exported	0	57.91	0	0	12.39	0	
Raw water retained	318.01	815.07	48.69	16.91	609	212.57	
Raw water imported	12.39	0	0	0			
Raw water collected	330.4	815.07	48.69	16.91	609	212.57	
Raw water losses	-3.8	7.03	3.15		18.63	0.37	
Raw water operational use	0	42.89	1.18	0.34	4.36	1.99	
Non potable supplies	0	0	0	0	0.19	0	
Raw water into treatment	334.2	765.15	44.36	16.57	585.82	210.21	
POTABLE WATER TO POINT OF DELIVERY							
Treatment works losses	0	7.67	0.66	0	5.02	0.6	
Treatment works operational use	0	0	0	0	6.17	0	
Potable water produced	334.2	757.48	43.7	16.57	574.63	209.61	
Potable water imports	0	17.94	4.13	7.94	85.8	1.19	
Potable water exports	26.76	15.72	6.63	0	17.53	3.82	
Distribution Input	295.91	741.09	41.86	24.9	641.91	206.02	
Distribution losses	52.85	128.39	9.76	9.81	129.29	36.83	
Water taken	243.06	612.7	32.1	15.09	512.62	169.19	
Distribution system operational use	0.64	1.57	0.11	0.05	1.33	0.43	
Water delivered	242.42	611.13	31.99	15.04	511.29	168.76	
POTABLE WATER CUSTOMER BASE							
Unmeasured household - population	932.414	2,067.75	103.59	45.263	1,653.48	547.31	
Unmeasured household - properties	366.859	871.608	39.863	16.152	678.82	232.3	
Unmeasured household - occupancy rate	2.54	2.37	2.6	2.8	2.44	2.36	
Measured household - population	188.593	773.699	25.201	19.632	682.115	239.39	
Measured household - properties	82.355	337.86	11.005	8.573	297.867	104.54	
Measured household - occupancy rate	2.29	2.29	2.29	2.29	2.29	2.29	
Unmeasured non-household population	0	0	0	0	0	0	
Unmeasured non- household properties	2.345	5.306	0.415	0.157	4.106	1.287	
Measured non-household population	17.246	52.391	2.394	1.644	41.399	14.812	
Measured non-household properties	21.157	70.098	4.154	3.167	63.42	21.593	
Total population	1,138.25	2,893.84	131.18	66.539	2,376.99	801.51	
Void household properties	18.269	37.967	1.43	0.747	26.388	9.37	
Void non household properties	3.887	10.568	0.531	0.347	9.197	3.225	
Total properties	494.872	1,333.41	57.398	29.143	1,079.80	372.32	
POTABLE WATER DELIVERED							
Water taken unbilled	4.3	10.08	0.65	0.27	8.37	2.73	
Water delivered billed	238.12	601.05	31.34	14.77	502.92	166.03	
Unmeasured household water delivered	154.67	338.31	19.85	6.45	273.89	89.67	
Unmeasured household - uspl	17.17	39.51	2.06	0.58	31.26	10.58	
Unmeasured household - consumption	137.5	298.8	17.79	5.87	242.63	79.09	
Unmeasured household - pcc	147.47	144.51	171.74	129.69	146.74	144.51	
Measured household water delivered	26.4	103.52	3.7	2.89	95.83	32.39	
Measured household -uspl	3.86	15.32	0.57	0.31	13.72	4.76	
Measured household - consumption	22.54	88.2	3.13	2.58	82.11	27.63	
Measured household - pcc	119.52	114	124.2	131.42	120.38	115.42	
Unmeasured non-household water delivered	2.01	4.52	0.36	0.13	3.5	1.1	
Unmeasured non-household - uspl	0.11	0.24	0.02	0.01	0.19	0.06	
Unmeasured non-household -consumption	1.9	4.28	0.34	0.12	3.31	1.04	
Measured non-household water delivered	55.04	154.7	7.43	5.3	129.7	42.87	
Measured non-household -uspl	0.99	3.18	0.21	0.11	2.92	0.98	
Measured non-household - consumption	54.05	151.52	7.22	5.19	126.78	41.89	
Void properties - uspl	1.04	2.2	0.1	0.04	1.64	0.57	
LEAKAGE							
Leakage	76.02	188.84	12.72	10.86	179.02	53.78	
Total leakage	153.62	141.62	221.61	372.65	165.79	144.45	

Figure 2A-2: Table 10B(i). Non financial measures; Environment Agency data; STW 2007

Appendix 3: OFWAT June Return; Table D; STW 2007

OPERATING EXPENDITURE/PROPERTY ANALYSIS						
1 Base service - operating expenditure/property served	£/prop	56.94	60.17	66.5	67.17	71.46
2 Enhanced service - additional operating expenditure/property served	£/prop	0.294	0	0	0	0
3 Supply/demand balance - additional operating expenditure/property served	£/prop	0.377	0	0.371	0.944	1.917
4 Quality enhancements - additional operating expenditure/property served	£/prop	1.18	0	0.09	0.13	0.31
5 New outputs/obligations - additional operating expenditure/property served	£/prop	0	0	0.22	0.17	0.17
6 Water service - total operating expenditure/property served	£/prop	58.79	60.17	67.18	68.41	73.87
CAPITAL EXPENDITURE/PROPERTY ANALYSIS						
7 Base service- capital maintenance expenditure/property served (infra and non-infra)	£/prop	34.23	24.33	22.44	32.79	39.65
8 Enhanced security of supply - additional capital expenditure/property served	£/prop	0	0	0	0.14	1.281
9 Improving and maintaining supply/demand balance - additional capital expenditure/property served	£/prop	4.539	5.146	7.107	5.659	9.055
10 Quality enhancements - additional capital expenditure/property served	£/prop	18.15	13.91	6.31	7.32	10.87
11 New outputs/obligations - additional capital expenditure/property served	£/prop	0	0	0.14	0	0
12 Water service - total capital expenditure/property served	£/prop	56.93	43.39	36.01	45.91	60.85
CAPITAL WORKS ACTIVITY						
13 Number of existing water treatment works refurbished for maintenance	nr	8	6	17	5	3
14 Capacity of refurbished water treatment works for maintenance	MI/d	88	4	956	11.3	0
15 Mains relined	km	101	124.6	9.7	0	0
16 Mains renewed	km	410.1	373	164	267	335.65
17 Total mains relined and renewed	km	511.1	497.6	173.7	267	335.65
WATER BALANCE						
18 Distribution input	MI/d	1,929.02	1,966.61	1,924.94	1,946.36	1,952.68
19 Total leakage	MI/d	513.77	512.01	502.02	541.95	523.83
20 Total savings achieved/assumed	MI/d	6.6	6	2.75	5.21	7.34
21 Water delivered	MI/d	1,611.94	1,654.51	1,625.80	1,617.00	1,579.79
22 Security of supply index - company's planned levels of service	nr	71	88	89	84.12	80.75
23 Security of supply index - reference levels of service	nr	71	88	89	84.12	80.75
METERING						
24 Number of household meters renewed	nr				41,191	91,780
25 Meter optants installed	nr				32,770	38,594
26 Selective meters - installed	nr				0	0
27 Percentage of households metered	%	21.7	22.96	24.23	25.92	27.63
OTHER KEY SUPPORTING INFORMATION						
28 GSS - Total number of payments made: water and (sewerage) service	nr	2,788	1,923	1,196	1,501	10,707
29 Customers on the special assistance register	nr	15,750	6,539	10,371	10,920	12,152
30 Total revenue outstanding < 48 months as % of annual forecast revenue	%			12.72	11.48	13.27
31 Average connected properties - water (excluding void properties)	0	3,203	3,224	3,245	3,255	3,245

Figure 2A-3: Table D. Boards overview, water service - key supporting information; STW 2007

Appendix 4: Composite Results Table Cranfield Laboratory Tests

Filename	Vcc	Nom flow (m3/hr)	Actual velocity (m/s)		Calibration correction	Mean Error Aquamaster	Normalised Std %Error		Standard Deviation		No. of points in run		Description	Run time (sec)
mm * or am*	Vac/Bat		Magmaster	Aqua Master	Magmaster	(percent)	Aqua Master	Magmaster	Aqua Master	Magmaster	Aqua Master	Magmaster		
mm118j01	Vac	143.06	5.0597	5.0943	1.0000	0.685	0.75	0.14	3.81E-02	6.86E-03	318	1202	AM stopped early after 316sec.	1200
mm18j01r	Vac	143.19	5.0642	0.0010	1.0000	-99.980		0.13		6.83E-03	nil	318	Setup run. No AM data logged.	0
j1802	Vac	52.44	1.8546	1.8580	1.0000	0.184	0.62	0.35	1.15E-02	6.53E-03	268	1201		1200
j1803	Vac	31.55	1.1160	1.1197	1.0000	0.331	0.55	0.26	6.11E-03	2.89E-03	567	901	AM log truncated.	900
j1804	Vac	8.64	0.3057	0.3062	1.0000	0.168	1.66	0.57	5.09E-03	1.73E-03	623	901	AM log truncated@ approx 16:19:1	900
j1805	Bat	8.62	0.3048	0.3058	1.0000	0.327	3.28	0.50	1.00E-02	1.53E-03	622	901	AM log truncated@ approx 16:41:0	900
j1806	Vac	1.84	0.0652	0.0652	1.0000	0.038	7.31	2.68	4.76E-03	1.74E-03	633	901		860
j1807	Bat	1.92	0.0678	0.0673	1.0000	-0.623	15.20	2.17	1.02E-02	1.47E-03	636	900		900
j1808	Vac	0.89	0.0314	0.0311	1.0000	-0.732	14.86	4.66	4.62E-03	1.46E-03	637	901		900
j1809	Bat	0.86	0.0306	0.0302	1.0000	-1.322	28.06	4.58	8.46E-03	1.40E-03	638	901		900
j1810	Vac	0.29	0.0102	0.0101	1.0000	-1.295	54.79	13.47	5.52E-03	1.38E-03	643	902	AM log truncated@ approx 18:38:03	900
j1811	Bat	0.28	0.0097	0.0073	1.0000	-24.502	104.23	14.22	7.66E-03	1.38E-03	645	900		900
j1812	Bat	0.59	0.0207	0.0203	1.0000	-1.958	29.62	7.11	6.01E-03	1.47E-03	637	843		900
j1813	Vac	0.58	0.0203	0.0198	1.0000	-2.672	17.29	7.13	3.42E-03	1.45E-03	645	900		900
j1902	Vac	0.03	0.0013	0.0010	1.0000	-23.396	247.03	57.79	2.50E-03	7.63E-04	3979	4202	Zero runs.	4200
j1903	Bat	59.34	2.0900	2.0989	1.0000	0.425	1.79	0.19	3.75E-02	3.96E-03	892	901		900
j1904	Bat	29.70	1.0469	1.0503	1.0000	0.324	1.22	0.42	1.28E-02	4.36E-03	858	900		900
j1905	Bat	8.93	0.3150	0.3160	1.0000	0.322	1.88	0.52	5.93E-03	1.63E-03	858	900		900
j1906	Vac	8.90	0.3140	0.3148	1.0000	0.250	1.10	0.49	3.46E-03	1.54E-03	852	901		900
j1907	Vac	3.43	0.1215	0.1212	1.0000	-0.229	2.89	1.17	3.51E-03	1.43E-03	852	900		900
j1908	Bat	3.42	0.1211	0.1209	1.0000	-0.182	5.05	1.25	6.11E-03	1.51E-03	859	901		900
j1909	Bat	2.10	0.0744	0.0744	1.0000	0.024	8.02	2.04	5.97E-03	1.52E-03	858	901		900
j1910	Vac	2.09	0.0742	0.0741	1.0000	-0.144	4.76	1.99	3.53E-03	1.48E-03	741	900	AM log truncated	900
j1911	Vac	0.88	0.0310	0.0310	1.0000	-0.102	10.65	4.98	3.30E-03	1.54E-03	852	901		900
j1912	Bat	0.87	0.0311	0.0306	1.0000	-1.566	20.56	5.02	6.29E-03	1.56E-03	859	901		900
j1913	Vac	0.64	0.0226	0.0225	1.0000	-0.357	14.78	7.10	3.33E-03	1.60E-03	852	900		900
j1914	Bat	0.63	0.0223	0.0224	1.0000	0.352	28.43	7.43	6.37E-03	1.66E-03	859	901		900
j1915	Vac	0.35	0.0130	0.0125	1.0000	-3.938	27.93	11.99	3.50E-03	1.56E-03	1137	1201		1200
j1916	Bat	0.33	0.0127	0.0118	1.0000	-7.445	65.79	11.01	7.76E-03	1.40E-03	1144	1201		1200
j1917	Vac	0.12	0.0045	0.0042	1.0000	-8.332	88.82	35.48	3.70E-03	1.61E-03	1788	1892	Approx start time	2010

Example of composite results table: Cranfield laboratory tests on battery EFM flowmeter

Appendix 5: Battery EFM Performance Specification

The meter under test during the performance tests in the Cranfield flow laboratory was a 100mm, battery EFM meter, serial number V/00194/3/1 from ABB. The manufacturer advertises the product as purpose designed for water industry application and is offered as a competitor to the traditional mechanical Woltmann type of network meter, commonly known in the UK as Helix meters.

ISO 4064, as published at the time of the tests, had three maximum permissible error (MPE) bands defining meter Classes A, B and C. The battery EFM manufacturer claimed an enhanced performance for the battery EFM when compared with ISO 4064 Class C, with additional accuracy should the unit be purchased and operated as mains powered. The comparative performance limits for both the battery EFM, the mains powered EFM and the extant ISO 4064 specification are given below.

Flowrate Q	ABB	ABB	Class	Class	Class	Meter Type + MPE	Flowrate/Qn	Velocity
m ³ /hr	Mains	Battery	C	B	A	Accuracy breakpoints	dimensionless	m/sec
0.1500	5					ABB Mains; Qmin	0.0025	0.0053
0.3599	5					ABB Mains; Q2%t &	0.0060	0.0127
0.3600	2	5	5			Class C; Qmin	0.0060	0.0127
0.8994	2	5	5				0.0150	0.0318
0.9000	2	2	2			Class C; Qt	0.0150	0.0318
1.8000	2	2	2	5		Class B; Qmin	0.0300	0.0637
2.9994	2	2	2	5			0.0500	0.1061
3.0000	0.25	2	2	5		ABB Mains; Q0.25%t	0.0500	0.1061
4.8000	0.25	2	2	5	5	Class A; Qmin	0.0800	0.1698
8.9990	0.25	2	2	5	5		0.1500	0.3183
9.0000	0.25	0.5	2	5	5	ABB battery; Q0.5%t	0.1500	0.3183
11.9994	0.25	0.5	2	5	5		0.2000	0.4244
12.0000	0.25	0.5	2	2	5	Class B; Qt	0.2000	0.4244
17.9994	0.25	0.5	2	2	5		0.3000	0.6366
18.0000	0.25	0.5	2	2	2	Class A; Qt	0.3000	0.6366
36.0000	0.25	0.5	2	2	2		0.6000	1.2732
48.0000	0.25	0.5	2	2	2		0.8000	1.6977
60.0000	0.25	0.5	2	2	2	Qn, 100mm all designs	1.0000	2.1221
120.0000	0.25	0.5	2	2	2	Qmax, 100mm all designs	2.0000	4.2441

Note: The ISO requirement is symmetric. However, only the +ve MPE limits are shown above

Specification for 100mm battery EFM from ABB, contrasted with ISO 4064 Classes A, B and C

A summary of the above table reads as follows:

When mains powered, the 100 mm EFM from ABB claims:

- an MPE of 0.25 % in the upper zone from 3 m³/h to 9.0 m³/h compared with the ISO 4064 class C figure of 2.0%;
- an MPE of 2.0 % covering all of the lower zone: compared with the ISO 4064 class C figure of 5.0 %.
- an MPE of 5.0 % extending below the ISO 4064 class C Qmin of 0.36 m³/h, down to a Qmin of 0.15 m³/h.

When battery powered, the 100mm EFM from ABB claims:

- (i) equivalent ISO 4064 Class C MPE's in the lower and upper zones of 5.0 % and 2.0 % respectively: up to a flowrate of 9.0 m³/h.
- (ii) an enhanced MPE of 0.5 % in the upper zone above 9.0 m³/h: compared with the ISO 4064 class C figure of 2.0 %.

The above technical description can be summarised graphically and is shown below:

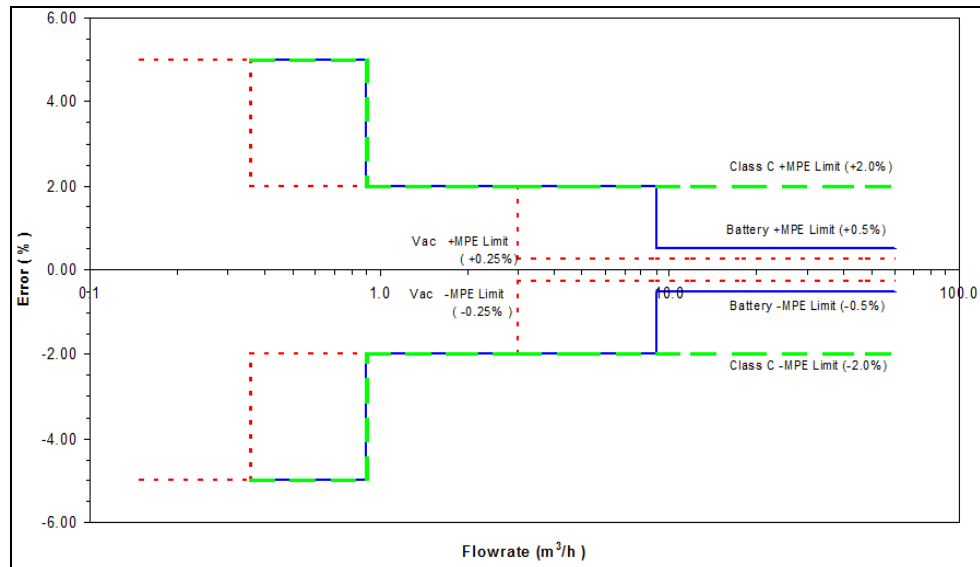


ABB mains (Vac) and battery EFM Maximum Permissible Errors (MPE's): as compared with ISO 4064 Class C MPE limits

Appendix 6: Meter Calibration Spreadsheet Input Example

Probe G 14848-1-1 and Tx 14848-1-1 07Sept 2005

	<u>FLOWMETER UNCERTAINTY</u>							
	<u>INPUT DATA</u>							
AquaProbe	G-14848-1-1	TX-14848-1-1						
	Calibrated on	07 September 2005						
				Units				
	x denotes:	Flowrate		litres/sec				
	y denotes:	Meter Factor						
Nom. Flow	Test points to be used		Test points to be omitted					x range
l/s	x	y		x	y			x
5				4.713	93.2		Min. x =	15
15	15.373	91.302					Max. x =	100
15	15.382	91.164						
25	25.267	91.126						
50	50.824	91.24						
50	50.833	91.355						
65.5	65.852	92.539						
65.5	65.852	92.374						
100	99.202	93.501						
150				143.39	96.363			
150				149.647	96.36			

Table 5A-1: Input sheet for data from calibration runs

Appendix 7: Plot of Meter Factor v Flowrate - Linear Fit, Mean Fit and Confidence Limits

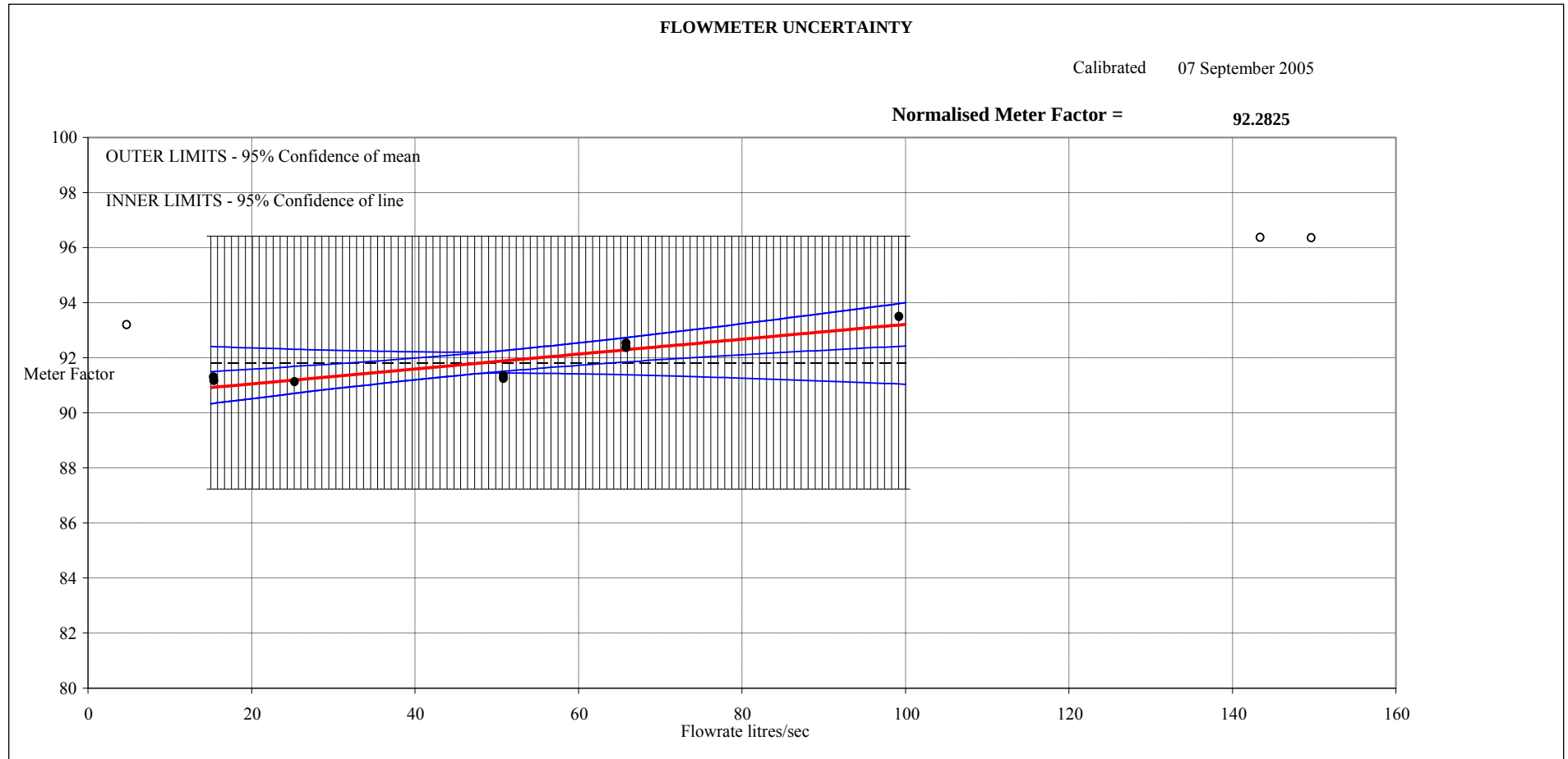


Figure 5A-1: Graph of linear-fit meter factor (red line); mean-fit (dotted line); confidence limits (blue lines) and +/-5% band (vertical lines)

Appendix 8: Flowmeter Characteristic Uncertainty

ASSESSMENT OF THE UNCERTAINTY OF THE FLOWMETER CHARACTERISTIC																			
0																			
Date Calibrated:		07 September 2005																	
The assessment is over a selected range and is either for an assumed linear characteristic or a constant characteristic i.e.:-																			
Meter Factor = $A + B \times \text{Flowrate} \pm \text{uncertainty}$ where A and B are linear regression constants calculated for the selected calibration points																			
or Meter Factor = Mean Meter Factor $\pm \text{uncertainty}$																			
The uncertainty of the linear characteristic is a combination of random uncertainty of the points and the uncertainty of the Calibration Facility ($\pm 0.1\%$). The uncertainty of the mean value, additionally includes the bias from the slope of the regression line. These uncertainty bands are illustrated graphically. The calculation methods are described in Section 14.9 of Appendix 4 of the Quality Manual and a copy of which is available on request.																			
Adopting a Linear Relationship calculation yields :-																			
		At Min.	At	At Max.															
		Range	Mean	Range	Max.														
Flowrate litres/sec		15.00	48.57	100.00															
Meter Factor		90.917994	91.825125	93.214656															
Random Uncertainty		0.63%	0.40%	0.85%															
Total (including lab.)		0.64%	0.41%	0.85%	0.85%														
From this calibration:- Uncertainty of meter characteristic over the given range will be no better than:-																			
<table border="1"> <thead> <tr> <th colspan="2">Meter Factor = $A + B \times \text{Flowrate} \pm U\%$ where:-</th> <th colspan="2">Normalised to STW Standard of 65.5 l/sec</th> </tr> </thead> <tbody> <tr> <td>A= 9.0513E+01</td> <td>U% = 0.85%</td> <td colspan="2">Calibrated Meter factor</td> </tr> <tr> <td>B= 2.7020E-02</td> <td></td> <td>=</td> <td>92.2825</td> </tr> </tbody> </table>								Meter Factor = $A + B \times \text{Flowrate} \pm U\%$ where:-		Normalised to STW Standard of 65.5 l/sec		A= 9.0513E+01	U% = 0.85%	Calibrated Meter factor		B= 2.7020E-02		=	92.2825
Meter Factor = $A + B \times \text{Flowrate} \pm U\%$ where:-		Normalised to STW Standard of 65.5 l/sec																	
A= 9.0513E+01	U% = 0.85%	Calibrated Meter factor																	
B= 2.7020E-02		=	92.2825																
Alternately, adopting a simple Mean Value calculation, not Normalised to a Standard Flow, yields																			
		At Min.	At	At Max.															
		Range	Mean	Range	Max.														
Flowrate litres/sec		15.00	48.57	100.00															
Meter Factor		91.825125	91.825125	91.825125															
Bias from slope		0.99%	0.00%	1.51%															
Total		1.63%	0.41%	2.37%	2.37%														
From this calibration:- Uncertainty of meter characteristic over the given range will be no better than:-																			
<table border="1"> <thead> <tr> <th colspan="2">Meter Factor = Mean Meter Factor $\pm U\%$ where:-</th> </tr> </thead> <tbody> <tr> <td>Mean = 9.1825E+01</td> <td>U% = 2.37%</td> </tr> </tbody> </table>								Meter Factor = Mean Meter Factor $\pm U\%$ where:-		Mean = 9.1825E+01	U% = 2.37%								
Meter Factor = Mean Meter Factor $\pm U\%$ where:-																			
Mean = 9.1825E+01	U% = 2.37%																		
N.B. The above uncertainties apply to the characteristic of the meter. The uncertainty of an isolated single measurement of flowrate using the meter is greater.																			

Figure 5A-2: Meter calibration summary sheet; includes linear-fit and mean-fit statistics

Appendix 9: Method of Analysis For Meter Factor Determination

The assessment of the flow-meter characteristic uncertainty is generated as part of the meter calibration summary sheet. The method used is given below, the basis of which may be found in reference 73, Coleman H.W. and Steele W.G.(1998) Experimentation and Uncertainty Analysis for Engineers; 2nd Ed; pp202 – 216.

The uncertainty assessment spreadsheet has been developed for use at Hams Hall calibration laboratory and is formally applicable to those particular flow conditions. A linear relation is assumed for the meter of the form: -

$$Y = A + B X$$

where X is a function of flow-rate, or of the Reynolds Number,
 Y is a meter coefficient, usually termed the meter factor, and
 A and B are constants.

A linear regression line is fitted to the set of n pairs of test points (x,y) that represent the selected range of X , and the regression constants A and B are calculated according to:

$$B = \frac{\sum xy - (1/n)(\sum x)(\sum y)}{\sum x^2 - (1/n)(\sum x)^2}$$

$$A = (1/n)\sum y - B(1/n)\sum x$$

Bands can then be plotted around the meter factor which describes the total uncertainty of the calculated linear characteristic. These curves differ from the regression line by $\pm U_T$, where U_T is a combination of both the random uncertainty of the line U_R

$$U_R^2 = t^2 \cdot \frac{\sum (y - A - Bx)^2}{n - 2} \cdot \left[\frac{1}{n} + \frac{(X - \bar{x})^2}{\sum x^2 - (1/n)(\sum x)^2} \right]$$

Plus the claimed uncertainty of the laboratory U_L . Unlike the conventional form of expressing U_R , in this analysis the uncertainty component multiplier is changed from the standard value of 2 and replaced with t , where t is student's t value at the 95% level.

$$U_T = \sqrt{U_R^2 + U_L^2}$$

This better reflects the distribution represented by the number of calibration test points; which is necessarily finite.

Where, instead of a linear-fit meter factor, a constant mean-fit relationship is used for the meter, then a bias b must be added to the uncertainty component. This represents the difference from the slope of the fitted line. Thus, for the mean-fit analysis

and

$$Y = \bar{y}$$

$$b = |B(X - \bar{x})|$$

When a single numerical value of uncertainty is quoted for the meter characteristic the maximum value of U_T should always be quoted. This value will occur at one limit for the range of X .

Appendix 10: Hams Hall Probe Calibration Procedure

Communicating and setting up the ABB battery EFM meter

The battery probe can be communicated with using HyperTerminal [53] or using the AutoRead software. Note that a number of parameters in the probe transmitter must be changed before calibration can commence.

The transmitter settings can be changed by using HyperTerminal but not AutoRead. The use of AutoRead is to both read and then save all the transmitter parameters of the probe so producing a record of the current state of the insertion probe meter set-up.

Communicating with the Transmitter using Hyperterminal:

- a. Link the transmitter with the PC and open the appropriate Comms. port using HyperTerminal.
- b. Press 'tab' to initiate a communication.

Communicating with the Transmitter using AutoRead:

- a. Create subfolder in 'As Found' with the name 'AutoRead as found [date]'.
- b. AutoRead can be found in [..\I+P SOFTWARE\AutoRead](#). Open AutoRead.
- c. Choose the correct comms. Port number and verify that it communicates with the probe transmitter. Input the information according to the prompted fields, setting the number of parameters to 350.
- d. Click on 'start'; assign a file name with 'Autoread' in the front, followed by the probe numbers, serial numbers, date and end with 'as found'. e.g. AutoRead-P009-g14848-3-1 05 Sep 2008 as found.
- e. Verify that the file is saved properly by opening it with MS Excel and save again as an ".xls" type file.

PROBE CALIBRATION PROCEDURE

- a. Connect the IPTS master meter serial output to the PC and verify the comms. Port number;
- b. Before switching the water on, insert probe onto the rig, ensure it is screwed tightly on.
- c. Remove the top of the probe. Firmly secure the digital probe position insertion indicator to the top of the probe.
- d. Push the probe down gently until it touches the bottom interior of the pipe.
- e. Reset the digital insertion probe position indicator.
- f. Place a marker around the probe to record the location of the probe relative to the pipe i.e. secure tape horizontally around the top of the probe assembly housing, taking care to maintain the marker parallel to the securing nut.
- g. Carefully withdraw the probe shaft out of the pipe using the two handles attached to the top box.
- h. Using the position indicator monitor the probe until it has been withdrawn by exactly the radius of pipe less 30mm i.e. for a pipe of diameter = 260mm, withdraw the probe by $(260/2 - 30) = 100\text{mm}$.
- i. Manually check that the probe is in the right place by using a rule to measure between the securing nut and the tape marker, so confirming the output of the probe position indicator.

Note: The above procedure should be done with the water on. If not, recheck all dimensions to ensure that the probe remains on the centre line.

- j. Ask the supervisor or a laboratory technician to turn on the flow and adjust to the flow rate set in the test schedule.
- k. Connect the PC to the probe and transmitter, verify the comm.
- l. Connect to probe via HyperTerminal. Make sure the variables battery probe variables are set as follows: >25=1; >195 = (do not change but leave in the as found state); >30=0.845; > 31=1.04879; >32=261.3; >117=0; >256=8.
Note: >30=Fp the profile factor; >31=Fi; the Insertion factor; >32=Di the pipe inner diameter.
- m. It is important to capture the text in Hyperterminal to file when changing these variables and write them down in a day book. Knowledge of the variables is required later in the process and is outlined later.
- n. Save the captured text in the “setup as cal folder”
- o. In the filename include the probe number, serial numbers, date and as cal setup at the end. eg. P024 g14848-8-1andtxg14848-8-1 as cal setup
- p. Run AutoCal, input the relevant information according to the probes’, the client’s and the rig’s details
- q. Name the save file as ‘S/N of probe, S/N for transmitter [date]’. [i.e. g14848-1-1andtxg14848-1-1 sat03sept05 run2.ipc] Save results in the ‘Probe Calibration Test Results [Date]’ folder.
- r. Set the time intervals between each points to > 911 millisecond for all flows.
- s. Copy out the results table to the day book, recording the number of data points used at each flow.

Nominal Flow rate (l/s)	Points	MUT (l/s)	MM1 (l/s)	Runtime (s)	Average error (%)	Meter factor
0	300					
100	300					
100	300					
65	300					
25	300					
15	400					
15	400					
5	500					
5	500					
65	300					

- t. When each run completes copy the ‘average flow for Mastermeter’, ‘average flow for probe’, ‘average error’, ‘run time’ and ‘meter factor’ to the day book as a backup to the electronic record held within the AutoCal program. These are used in conjunction with the meter calibration spreadsheet to produce the probe calibration graph, uncertainty and certificate.
- u. Ask the supervisor or a laboratory technician to adjust the flowrate to the next flow set in the test schedule.
- v. Stop the flow before changing the probe.

Appendix 11: Key Performance Information, Hams Hall 260mm Reference Line

Profile Reference	HH AutoProfile 1		HH AutoProfile 2		HH AutoProfile 3		HH AutoProfile 4		HH AutoProfile 5	
Profile Date	19-Oct-06		19Oct06 repeat		20Oct06lowflow		15-Dec-06		14-Jan-07	
Profile factor	0.8466		0.8286		0.8495		0.8441		0.8562	
NSE % - max	2.94	p7	2.05	p2	3.10	p11	4.06	p1	2.45	p1
- mean	1.86		1.28		1.97		2.02		1.29	
NSE % - min	1.17	p10	0.87	p3	1.04	p4	1.12	p6	0.83	p9
NSERelCL-max	1.79	p7	1.71	p2	1.68	p11	3.62	p1	2.03	p1
- mean	1.14		1.06		1.06		1.80		1.07	
NSERelCL-min	0.72	p10	0.73	p3	0.56	p4	1.00	p6	0.69	p9
Noise %	13.45	p5	8.89	p1	14.52	p11	21.31	p1	11.18	p1
- mean	7.85		5.80		9.36		9.43		5.32	
	5.07	p2	4.11	p5	5.31	p4	4.30	p6	3.06	p9
Stability %	9.65	p7	1.83	p3	2.43	p3	3.24	p2	1.18	p9
	1.83		0.67		-3.64		0.54		-0.20	
	-4.31	p3	-4.60	p1	-9.20	p11	-2.15	p7	-3.31	p2
Reproducibility										
Far Wall	0.76		0.81		0.27		0.13		0.34	
Centre Line	1.21		1.24		1.73		0.95		0.25	
Near Wall	0.53		0.16		1.71		2.17		0.46	
Max Expanded Uncertainty %	1.02	p7	0.72	p2	0.36	p4	0.39	p6	0.32	p2
- mean	0.65		0.44		0.68		0.70		0.55	
Min Expanded Uncertainty %	0.41	p10	0.30	p10	1.08	p11	1.41/3.45	p1/p1 1	1.05	p1
Variable Exp'd Uncertainty %	0.08 to 0.23	n=1	0.06 to 0.16		0.08 to 0.24		0.09 to 0.32		0.07 to 0.23	
Variable Exp'd Uncertainty %	0.19 to 0.51	n=5	0.13 to 0.36		0.18 to 0.54		0.77/ 0.19 to 3.45/ 0.71 See note		0.16 to 0.52	
Velocity Stats										
Far Wall	1.156		1.178		0.344		1.263		1.214	
P2	1.266		1.268		0.37		1.354		1.304	
Maximum	1.339	p4	1.332	p4	0.389	p4	1.425	p4	1.355	p4
Centre Line	1.261		1.288		0.373		1.366		1.29	
P10	0.998		0.995		0.304		1.066		1.028	
Near Wall	0.943		0.935		0.281		1.02		0.984	
NOTE: A temporary Signal drop-out caused velocities for four numbers to be lowered so affecting the Expanded Uncertainty										

Appendix 12: Key Hams Hall and ABB Velocity Profile Performance Information

Profile Reference	ABB 212mm 650b Rig AutoProfile		HH 260mm AutoProfile Long Term Average		ABB AutoProfile 1 (medium flow)		ABB AutoProfile 2 (high flow)		Ratio of 260/212	Ratio of 212/260	Ratio of 1195med/260	Ratio of 1195high/260
Profile Date	6-Apr-06		Oct06 - Jan07		28-Feb-07		28-Feb-07					
Profile factor	0.827		0.845		0.7831		0.8544					
NSE % - max	1.22	p8	4.06	p1	8.50	p1	9.10	p1	3.33	0.30	2.09	2.24
- mean	0.84		1.68		4.70		3.90		2.00	0.50	2.80	2.32
NSE % - min	0.56	p6	0.83	p9	2.20	p6	1.80	p7	1.48	0.67	2.65	2.17
NSErelCL-max	2.08	p8	3.62	p1	3.58	p1	4.90	p1	1.74	0.57	0.99	1.35
- mean	1.42		1.23		2.00		2.10		0.87	1.15	1.63	1.71
NSErelCL-min	0.96	p6	0.69	p9	0.92	p6	1.00	p7	0.72	1.39	1.33	1.45
Noise %	5.15	p8	21.31	p1	32.49	p1	31.12	p1	4.14	0.24	1.52	1.46
- mean	3.58		7.55		18.25		13.93		2.11	0.47	2.42	1.85
	2.25	p5	3.06	p9	8.46	p6	6.61	p8	1.36	0.74	2.76	2.16
Stability %	1.83	p9	9.65	p7	5.40	p3	5.20	p2	5.27	0.19	0.56	0.54
	0.41		-0.43		-1.10		0.60		-1.05	-0.95	2.56	-1.40
	-1.22	p1	-9.20	p11	-8.00	p7	-16.80	p1	7.54	0.13	0.87	1.83
Reproducibility												
Far Wall	0.36		0.47		1.04		0.89		1.31	0.77	2.21	1.89
Centre Line	0.07		1.076		1.26		1.00		15.37	0.07	1.17	0.93
Near Wall	0.18		1.01		4.07		1.52		5.61	0.18	4.03	1.50
Max Expanded Uncertainty %	0.47	p8	1.02	p7	3.33	p1	3.56	1	2.17	0.46	3.26	3.49
- mean	0.32		0.61		1.86		1.52		1.91	0.52	3.05	2.49
Min Expanded Uncertainty %	0.22	p6	0.3	p10	0.86	p6	0.72	p7	1.36	0.73	2.87	2.40
Variable Exp'd Uncertainty %	0.05 to 0.11	n=1	0.06 to 0.32	n=1	0.19 to 0.74	n=1	0.16 to 0.80					
Variable Exp'd Uncertainty %	0.10 to 0.24	n=5	0.13 to 0.52	n=5	0.43 to 1.66	n=5	0.36 to 1.78					

Summary velocity profile KPI statistics: 260mm Hams Hall line; 212mm ABB line and 1195mm ABB line

Appendix 13: Key Performance Information Profile Statistics, 314mm Chaddesley Corbett Gravity Outflow

Profile Reference	Chaddersley Corbett AutoProfile1 (Battery)		Chaddersley Corbett AutoProfile2 (dc)	
Profile Date	12-Feb-04		12-Feb-04	
Profile factor	0.9062		0.8274	
NSE % - max	12.63	p10	5.05	p1
- mean	5.87		2.44	
NSE % - min	2.24	p5	0.94	p6
NSErelCL-max	3.15	p10	5.4	p1
- mean	1.46		2.6	
NSErelCL-min	0.56	p5	1	p6
Noise %	31.44	p10	18.43	p1
- mean	15.46		10.39	
	5.31	p5	3.62	p6
Stability %	34.42	p1	9.61	p11
	4.06		0.39	
	-8.19	p8	-4.07	p9
Max Expanded Uncertainty %	4.4	p10	1.76	p10
- mean	2.04		0.85	
Min Expanded Uncertainty %	0.78	p5	0.33	p6
Variable Exp'd Uncertainty %	0.17 to 0.98	n=1	0.07 to 0.39	
Variable Exp'd Uncertainty %	0.39 to 2.20	n=5	0.16 to 0.88	
Velocity Stats				
Far Wall	0.8912		0.834	
P2	1.0591		0.995	
Maximum	1.202	p10	1.0977	p5
Centre Line	1.1075		1.0968	
P10	1.202		0.947	
Near Wall	1.0263		0.8712	

Summary KPI statistics profile: 314mm Chaddesley Corbett gravity outflow

Appendix 14: Probe Vibration and Velocity Limit Calculation Spreadsheet Sample

Definition of Input Variables re Physical Location									
Manf A gland length	209.5		Outer diameter probe tube (m)	0.02	0.01				
Tapping length	200		Inner diameter probe tube (m)	0.018	0.009				
Actual total length	409.5		I	2.70098E-09					
Frequency limit settings	low 0.6		E	2.00E+11					
	high 1.3								
Vibration Calculation for portion of probe inserted into the pipe section									
Operator insertion length - i.e. the physical protrusion into the pipe	Physical length, incl fittings etc representing the true unsuspended probe insertion length	Turner's frequency formula (empirical)	Velocity generated from Strouhal number formula	Arbitrary low frequency limit	Velocity equivalent at low frequ limit	Arbitrary high frequency limit	Velocity equivalent at high frequency limit	Total drag at Strouhal base velocity	Deflection based on momentum destruction
								drag W	tip deflection (mm)
Insertion length	length to support clamp	Freq(int) -inside frequency	velocity for inside freq	low frequency boundary	v for lowf	high frequency boundary	v for highf	pav ² /L	
mm	mm	hz	m/s	hz	m/s	hz	m/s		mm
50	459.5	76.7	7.28	46.00	4.37	99.66	9.47	1061	0.00
100	509.5	62.2	5.91	37.31	3.54	80.84	7.68	698	0.02
150	559.5	51.4	4.89	30.87	2.93	66.88	6.35	478	0.06
200	609.5	43.3	4.11	25.95	2.47	56.23	5.34	338	0.13
250	659.5	36.9	3.50	22.12	2.10	47.93	4.55	245	0.22
300	709.5	31.8	3.02	19.08	1.81	41.34	3.93	182	0.34
350	759.5	27.7	2.63	16.62	1.58	36.01	3.42	138	0.48
400	809.5	24.3	2.31	14.61	1.39	31.65	3.01	107	0.63
450	859.5	21.6	2.05	12.94	1.23	28.03	2.66	84	0.80
500	909.5	19.2	1.83	11.54	1.10	24.99	2.37	67	0.97

Vibration and velocity limit calculation

Step 1: Define the probe length and all fittings needed to calculate the true insertion length relative to the probe point of suspension, as well as the length of the probe supported outside the pipe assembly.

Step 2: Use the empirical expressions from Turner to generate the approximate fundamental frequency of vibration for different probe sizes with incremental, increasing, steps of the probe insertion into the pipe.

Step 3: Use the point of critical vortex shedding, determined by the Strouhal number, to calculate an equivalent velocity which matched that of the fundamental frequency of vibration – inside and outside the pipe.

Step 4: Allocate safety limits (arbitrary), to allow both for the considerable approximations made and for the variations in physical installation of the probe fixing which occur with differing installers. Typically de-rating safety values are 30% outer frequency and 40% inner frequency.

Appendix 15: Maximum Likelihood Estimation (MLE)

The following sets out the mathematics behind the method of maximum likelihood estimation which is used to adjust the component parts of a water balance table in accordance with OFWAT's June return report requirements and definitions manual [26] and UKWIR report 99/WM/08/25 [87].

Let C_i be the components of demand, and DI the distribution input. Suppose these are each measured with a given certainty. Assuming that the uncertainty is normally distributed, then we can write:

$$C_i \sim N(\mu_i, \sigma_i^2) \quad (i = 1, \dots, n)$$

$$\text{and } D \sim N(\mu_D, \sigma_D^2)$$

The μ_i and μ_D are our estimates and the σ_i and σ_D are proportional to the uncertainty. (Note that the constant of proportionality depends on the confidence with which the uncertainty interval is given). As long as the same confidence level is used every time then we can use a constant of proportionality of 1.

Remember that the goal is to produce “adjusted” estimates of ν_i (for the C_i), and ν_D (for the DI), so that $\sum_{i=1}^n \nu_i = \nu_D$. The MLE for ν_i and ν_D is calculated as follows:

$$\text{For } X \sim N(\mu, \sigma^2) \text{ the density function is } f_x(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\left[\frac{(x-\mu)^2}{2\sigma^2}\right]}$$

Thus the likelihood function for $(C_1 = \nu_1, C_2 = \nu_2 \dots C_n = \nu_n, D = \nu_D)$ is:

$$F_R(\nu_i, \nu_D) = \left[\prod_{i=1}^n \frac{1}{\sigma_i \sqrt{2\pi}} e^{-\left[\frac{(\nu_i - \mu_i)^2}{2\sigma_i^2}\right]} \right] \frac{1}{\sigma_D \sqrt{2\pi}} e^{-\left[\frac{(\nu_D - \mu_D)^2}{2\sigma_D^2}\right]}$$

where the ν_i and ν_D are chosen to balance the distribution and demand. The aim is to chose ν_i and ν_D so maximizing F_R (the MLE) but subject to the constraint that

$$\sum_{i=1}^n \nu_i - \nu_D = 0$$

Taking logs to make the algebra easier, one obtains

$$\ln(f_R) = (n+1) \ln\left(\frac{1}{\sqrt{2\pi}}\right) + \sum_{i=1}^n \ln\left(\frac{1}{\sigma_i}\right) + \ln\left(\frac{1}{\sigma_D}\right) + \sum_{i=1}^n \left(-\frac{(\nu_i - \mu_i)^2}{2\sigma_i^2}\right) - \frac{(\nu_D - \mu_D)^2}{2\sigma_D^2}$$

Next, note that the first three terms on the RHS are constant with respect to v_i and v_D . Thus, after changing the sign of the v_i and v_D dependant parts, the problem becomes equivalent to maximizing:

$$L_o = \sum_{i=1}^n \left(\frac{(v_i - \mu_i)^2}{\sigma_i^2} \right) + \frac{(v_D - \mu_D)^2}{\sigma_D^2}$$

Subject to the previously stated constraint that

$$\sum_{i=1}^n v_i - v_D = 0$$

By introducing the Lagrange multiplier λ

$$L_o = \sum_{i=1}^n \left(\frac{(v_i - \mu_i)^2}{\sigma_i^2} \right) + \left(\frac{(v_D - \mu_D)^2}{\sigma_D^2} \right) + \lambda \left(\sum_{i=1}^n v_i - v_D \right)$$

Given that we want $\frac{\partial L}{\partial v_i} = 0 (i = 1, \dots, n)$, $\frac{\partial L}{\partial v_D} = 0$, $\frac{\partial L}{\partial \lambda} = 0$

$$\frac{\partial L}{\partial v_i} = 0 \Rightarrow \frac{2(v_i - \mu_i)}{\sigma_i^2} + \lambda = 0 \Rightarrow v_i = \mu_i - \frac{\lambda \sigma_i^2}{2} \quad (1) \text{ and}$$

$$\frac{\partial L}{\partial v_D} = 0 \Rightarrow \frac{2(v_D - \mu_D)}{\sigma_D^2} - \lambda = 0 \Rightarrow v_D = \mu_D - \frac{\lambda \sigma_D^2}{2} \quad (2)$$

$\frac{\partial L}{\partial \lambda} = 0$ i.e. the constant holds. Using (1) and (2) above λ can be substituted so that

$$\sum_{i=1}^n \left(\mu_i - \frac{\lambda \sigma_i^2}{2} \right) = \left(\mu_D - \frac{\lambda \sigma_D^2}{2} \right) \Rightarrow \lambda = \frac{2 \left(\sum_{i=1}^n \mu_i - \mu_D \right)}{\sum_{i=1}^n \sigma_i^2 + \sigma_D^2}$$

Which means that v_i and v_D can then be expressed in terms of the original means and standard deviation as follows :

$$v_i = \mu_i - \sigma_i^2 \frac{\left(\sum_{i=1}^n \mu_i - \mu_D \right)}{\sum_{i=1}^n \sigma_i^2 + \sigma_D^2},$$

$$v_D = \mu_D + \sigma_D^2 \frac{\left(\sum_{i=1}^n \mu_i - \mu_D \right)}{\sum_{i=1}^n \sigma_i^2 + \sigma_D^2}$$

Appendix 16: Battery EFM Insertion Probes; Examples of Tip Condition



Figure 9A-1: Ex factory, new probe tip condition



Figure 19A-2: Ex field after 6months profiling/verification use; note change to the geometry of the tip end with flattening of the radial curvature

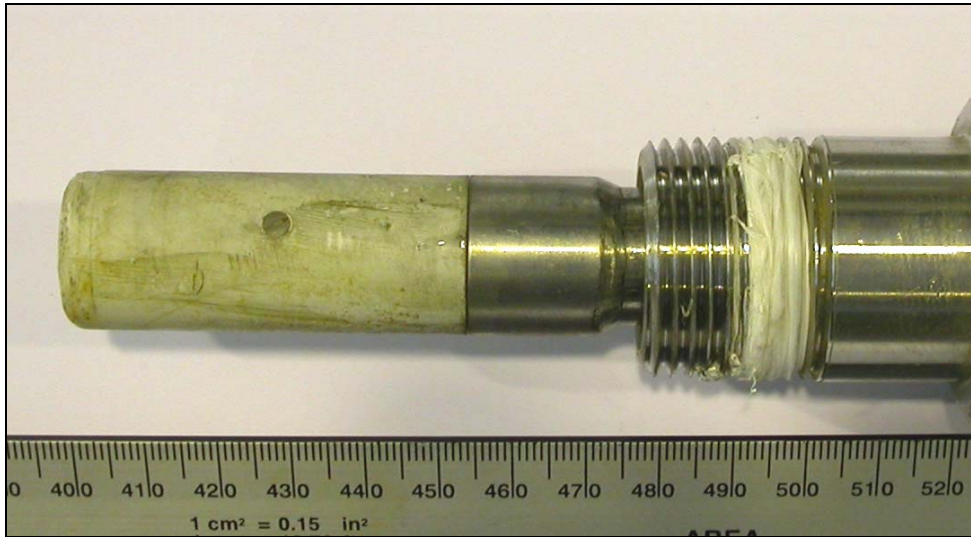


Figure 9A-3: Ex field after 12months profiling/verification use; note significant surface scratching, cracking and flattening of tip end radial curvature



Figure 9A-4: Ex field after 3 years profiling/verification use; splitting of probe tip end seal revealing the internal manufacturing 'O' ring seal