# Recommended Practice for the Design, Testing, and Operation of Subsea Multiphase Flow Meters

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## Introduction

Multiphase flow is a complex fluid phenomenon presenting many observable and distinctly different spatial patterns. These flow regimes are a function of fluid composition, velocity, flow orientation, geometry and operating conditions. This characteristic of multiphase flow creates a greater number of variables requiring measurement than seen in single phase flow. Multiphase flow meters (MPFMs) tend to use a combination of measurement principles and software models to delineate component parameters of the specific flow condition undergoing measurement. These elements are further combined to simultaneously resolve the total flow state and inform the user of the flow rate of each phase.

This document is intended for use by persons familiar with the principles of multiphase flow and the technologies used to measure its constituent parts. It is the intent of this Recommended Practice (RP) to outline a strategy for the correct sizing, specification, integration, and testing of MPFMs to maximize their performance for a specific application. Measurement techniques used in MPFMs are every bit as complex as the flow itself and only brief descriptions are included herein. It is recommended that the reader be acquainted with API *MPMS* Ch. 20.3 which describes in detail the technologies of multiphase metering, calibration, measurement uncertainty, and operation. API *MPMS* Ch. 20.3 referred to in various parts of this document wherein the reader should seek further information or best practice. API *MPMS* Ch. 20.3 is not specific to subsea applications and some topside measurement methods are included.

Various expertise is required throughout the life cycle of the MPFM to achieve optimal performance. Due to the number of interfaces and design parameters an appropriate strategy is required to ensure the meter is appropriate for its specific application. This RP acts as a guide for the responsible engineer outlining key parameters of the plan that quantifies meter performance based on application, sizing data, technology constraints, and performance checks through supplier, independent facilities, and in situ tests.

There is a distinct separation in ownership between MPFM specification, testing, and installation versus commissioning and operation. This RP addresses equipment design in Section 4 to Section 8 and commissioning/ operational issues in Section 9 and Section 10. To ensure accuracy and functionality of the MPFM, there should be a coherent handover between equipment design and long term operation. A number of operational issues are addressed in this RP, as well as metering methodologies, but these are only intended as suggested interfaces that should be addressed by the responsible engineer. This RP should be used in combination with appropriate measurement and operational standards to develop a comprehensive strategy for the design, installation, and long term operation of an MPFM.

# Recommended Practice for the Design, Testing, and Operation of Subsea Multiphase Flow Meters

## 1 Scope

This document provides recommendations for the sizing, specification, system integration, and testing of subsea flow meters [henceforth referred to as multiphase flow meters (MPFMs)] for measurement of full stream, multiphase flow. This Recommended Practice (RP) includes wet gas flow meters as a subset of MPFMs. In-line MPFMs are typically used in subsea applications and are the focus of this RP.

These recommendations and guidelines are intended for use by the engineer responsible for the delivery of the MPFM. Due to the nature of multiphase flow measurement it is anticipated that a cross-disciplinary team may be involved throughout its deployment and operational life.

## 2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

API *Manual of Petroleum Measurement Standards* (*MPMS*), Chapter 20.3, *Measurement of Multiphase Flow*

API Specification 6A, *Specification for Wellhead and Christmas Tree Equipment*

API Specification 17D, *Design and Operation of Subsea Production Systems—Subsea Wellhead and Tree Equipment*

API Standard 17F, *Standard for Subsea Production Control Systems*

API Recommended Practice 17N, *Recommended Practice for Subsea Production System Reliability and Technical Risk Management*

## 3 Terms, Definitions, Acronyms, and Abbreviations

### 3.1 Terms and Definitions

For the purpose of this document the following terms and definitions apply. For consistency, these are identical to those used in API *MPMS* Ch. 20.3.

**3.1.1**
**accuracy**
The degree of conformity of a measurement to a known standard for the unit of measurement.

**3.1.2**
**actual conditions**
**measurement conditions**
**line conditions**
**flowing conditions**
Conditions of pressure and temperature of the fluid at the point where fluid properties or flows are measured.

**3.1.3**
**allocation**
The mathematical process of determining the proportion of produced fluids from individual entities (zones, wells, fields, leases, or producing units) when compared to the total production from the entire system (reservoir, production system, and gathering systems).

**3.1.4**
**availability**
The ability of an item to be in a state to perform a required function under given conditions at a given instant of time, or in average over a given time interval, assuming that the required external resources are provided.

NOTE High availability can be achieved through high reliability (equipment rarely breaks down) or maintainability (when equipment breaks down it is repaired quickly) or a combination of both.

**3.1.5**
**calibration**
Comparison and adjustment to a standard of known accuracy.

**3.1.6**
**fiscal**
Of or relating to financial matters; with respect to measurement, those that have a financial impact on custody transfer, allocation, royalty, or taxation.

**3.1.7**
**fiscal measurement**
Measurement systems and procedures required to determine a quantity that may be expected to have a direct financial impact to affected parties (contrast this with custody transfer measurement).

**3.1.8**
**flow regime**
The physical geometry exhibited by a multiphase flow in a conduit; the geometrical distribution in space and time of the individual phase components, i.e. oil, gas, water, any injected chemicals, etc.

NOTE For example, liquid occupying the bottom of a horizontal conduit with the gas phase flowing above.

**3.1.9**
**phase**
A term used in the sense of one constituent in a mixture of several. In particular, the term refers to oil, gas, water, or any other constituent in a mixture of any number of these.

**3.1.10**
**pressure-volume-temperature**
**PVT**
The phase behavior and physical properties of hydrocarbon fluids at pressure and temperature.

NOTE Included are relative phase volume, gas-oil ratio (GOR), bubble point and hydrocarbon dew point, density, formation volume factors, compressibility, viscosity, and composition.

**3.1.11**
**redundancy**
Existence of more than one means to perform a required function (e.g. by duplicating items).

**3.1.12**
**reliability**
The ability of an item to perform a required function, under given conditions of production, environment, and usage, for a required time interval.

**3.1.13**
**responsible engineer**
The primary point of responsibility for the delivery and operation of the MPFM.

NOTE This task may also be assigned to a cross-functional team or split across multiple people.

**3.1.14**
**sampling**
The collection of production samples which may be taken topside or subsea and at actual or standard conditions.

**3.1.15**
**uncertainty**
The parameter, associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand (the value being measured).

NOTE See ISO/IEC Guide 98-3:2008 for a more complete definition.

**3.1.16**
**validation**
The process that substantiates whether technical data and engineering models are within the required range of accuracy, consistent with the intended application.

**3.1.17**
**verification**
The process that determines the extent to which a procedure, task, physical product, or model conforms to its specification.

**3.1.18**
**virtual meter**
Predictive well rate modeling (virtual flow metering system) is a well rate determination method that utilizes computer-based predictive flow modeling techniques in conjunction with real-time well/process sensor and instrumentation data for continuous multiphase well rate estimation.

**3.1.19**
**well test**
The execution of a set of planned data acquisition activities to broaden the knowledge and understanding of fluid phase rates and hydrocarbon properties of a producing well from a reservoir.

**3.1.20**
**well trajectory**
The trajectory of production parameters displayed by a well over time, sometimes shown in a flow or composition map.

**3.1.21**
**wet gas**
A subset of multiphase flow in which the dominant fluid is gas and in which there is a presence of some liquid.

## 3.2 Acronyms and Abbreviations

For the purposes of this document, the following acronyms and abbreviations apply.

| | |
|---|---|
| DP | differential pressure |
| EFAT | extended factory acceptance test |
| ESS | electrical stress screening |
| ETU | electrical test unit |
| FAT | factory acceptance test |
| FMECA | failure modes, effects, and criticality analysis |
| GOR | gas-oil ratio |
| MPFM | multiphase flow meter |
| MTBF | mean time between failure |
| PCB | printed circuit board |
| PSL | production specification level |
| PVT | pressure-volume-temperature |
| RIT | receive inspection test |
| ROV | remotely operated vehicle |
| RSO | Radiation Safety Officer |
| SAT | site acceptance test |
| SCM | subsea control module |
| SIT | system integration test |
| STP | standard temperature and pressure |

# 4 Multiphase Flow Meter (MPFM) Applications

## 4.1 General Uses

In subsea applications, MPFMs are normally used in well testing, allocation measurement, fiscal measurement, well management, and/or in flow assurance applications (see 3.1 for definitions). The categorization of MPFM application is important since it can be used to determine the required level of factory testing, independent verification, field maintenance, and ongoing verification required during operation.

Well testing is used to gather three phase flow rates in order to determine well productivity and life and is also used to enhance production. Enhancement generally requires understanding the influence of various operating parameters. An MPFM is used to either replace or supplement the topside test separator traditionally used in well testing. Replacing the test separator can reduce the topside payload and free up additional space.

An MPFM used in conjunction with a test separator can gather data regarding flowing conditions quicker than a test separator operating alone. In addition, it can give instantaneous data at the point of measurement. Test separators require extended periods to identify flow instabilities under changing conditions. For complete removal of the test separator the replacement MPFM should demonstrate similar measurement uncertainty as the separator. In addition, it should be subject to regular independent verification with fluid samples to confirm suitability of meter configuration parameters.

Allocation and fiscal measurements are used in conjunction with procedures for volume or financial calculation for ownership and thus require the lowest level of measurement uncertainty and repeatability, along with increased instrument calibration. To ensure an MPFM meets these strict requirements, flow tests across the range of operating conditions are recommended (see 8.5). The terms of any meter testing and fluid sampling required are often part of the associated operational contract.

Well management/flow assurance applications are defined by the need to track changes in fluid composition. Fluid phase changes are of particular concern in gas lift, water breakthrough, and some chemical injection applications. Tracking the difference between measurements over a period of time, rather than any individual measurement, is of greatest concern. Therefore the requirement for rigorous sampling, in situ calibration, and independent flow tests can be reduced.

For all potential applications, the uncertainty required from the meter should be determined from an appropriate study conducted on the flow assurance model of the system. The study should conclude with definitions of acceptable uncertainty across the volume fractions for specific flow conditions or well trajectories. From this study, the responsible engineer should define the specific requirements for uncertainty, repeatability, and reproducibility for the meter application. Validating stringent performance characteristics has an economic impact that needs to be justified by the criticality of the meter application.

## 4.2 MPFM Locations

The location of the MPFM is somewhat dependent on its intended application and the overall field layout. Location options include tree mounted units typically as part of a choke bridge/flow module/retrievable module, jumper mounted units, and placement in a manifold.

Generally, the meter application and equipment size influences or determines the best location. Dedicated MPFMs for individual wells can be located on the tree, connected jumper, or on an adjacent manifold for continuous measurement. Intermittent flow measurement can be accomplished at a manifold which accommodates direction of individual well streams through a single meter. The single meter can contain relevant PVT data for multiple wells. The specific well data can be utilized when a particular well is directed through the meter. This layout may not be suitable for continuous individual well tracking.

Individual meter costs and reliability may influence the decision of single versus multiple locations. Multiple meters may require additional operational management depending on application.

Access for installing and retrieving MPFMs and meter electronic modules should be considered in any field layout (see 7.3). Mechanical interfaces are detailed in 5.8. Intervention of tree and jumper mounted units may only affects production at that specific location. Retrieval of units from manifolds may require shut-in of multiple wells if a bypass is not available or working over adjacent structures is prohibited. This can be due to a situation in which double isolation and integrity assurance is not available. Manifold designs with bypass lines should ensure maximum production is maintained during meter shutdown or retrieval.

Recommendations for the flow geometry upstream and downstream are dependent on measurement technology, and are normally given by the supplier of the meter and should be considered as part of meter location. In addition, erosion concerns should be addressed in all applications, e.g. high velocity wet gas with potential for spiral flow. Consideration for meter location can also be affected by chemical injection point, piping configuration, and proximity to a flow restriction since this relates to meter performance (see 5.3 for further design parameters).

# 5 Design Criteria

## 5.1 Functional Specification

Since MPFMs use various measurement technologies to ascertain different parameters regarding the flow stream, there is no one standard technology. Users should become familiar with the various principles and measurement technologies as detailed in API *MPMS* Ch. 20.3. A functional specification for the meter should be provided by the manufacturer. This specification should detail the methodology used for determining the components of the multiphase flow undergoing measurement. The specific technologies used should be explained, and both their input requirements and resultant measurement should be defined. In addition, an outline of how the constituent flow rates are determined from meter in situ physical measurements, flow models, and configuration input parameters should be provided.

The elements of the flow computation process should be clearly illustrated. The functional specification should form the basis of meter sizing, performance testing, verification, and uncertainty determination based on the parameters used. The methodology for flow rate measurement should be detailed with measurement uncertainty defined based on input data, sensor calibration, flow model assumptions, and all other relevant unknowns. The responsible engineer should seek to understand the primary parameters involved in the flow calculation in cooperation with the equipment supplier.

Performance tests conducted at the manufacturer, third-party facilities, and in situ once installed should all tie back to the limits laid out in the functional specification. In addition, tests should be designed to verify the limits of the particular technology used, if suitable representative conditions cannot be replicated.

## 5.2 Governing Specification

The design, manufacture, and factory acceptance testing of MPFMs shall adhere to the following standards in addition to vendor, local government, and project specific requirements:

— API 6A,

— API 17D,

— API 17F.

## 5.3 Standard Meter Design Parameters

MPFMs are designed in accordance with API 17D service conditions and product specification levels. Relevant information for meter specification includes pressure rating; temperature classification; sour service designation and marking; and product specification level.

As a minimum, the responsible engineer should supply the following to the meter supplier:

— desired/required design life;

— meter location, orientation, and expected piping configuration;

— water depth;

— explicitly state production case flow rate estimates for oil, water, and gas;

— expected flowing pressure and temperature for various production cases over the meter life including shut-in pressure and temperature, as well as flowing pressure and temperature at the meter location for various production cases;

— expected sand production rates;

— potential changes in production cases due to enhanced oil recovery techniques or water breakthrough;

— field life, i.e. expected meter life without planned maintenance accounting for erosion, corrosion, fatigue, and all associated failure modes;

— any specific shutdown/start-up scenarios that effect the MPFM including injection of hydrate inhibitor, variance in gas lift, changes in water injection, and local injection of other chemical inhibitors;

— fluid composition to confirm material compatibility and sour service designation; indicate the possible presence of wax/asphaltenes that can adhere to adjacent surfaces; and indicate any possible fluid property effects (e.g. emulsion viscosity) that can impact MPFM measurement performance;

— fluid properties should be made available for meter configuration parameters including relevant PVT data and other meter type specific input parameters;

— interface with the production system including material interfaces, control system, power, and equipment retrieval.

All relevant flow assurance studies should be made available to the meter manufacturer where possible, including the system sensitivity study referenced in 5.5. This may include fluid information for PVT and equation of state modeling if available. Changes to the production profile and salinity due to water breakthrough, increased gas lift, and commingling from other wells and production zones can affect both meter models and configuration parameters.

## 5.4 Meter Sizing

Due to the numerous measurement technologies applied in multiphase flow measurement, sizing data are used in various different ways. All technologies share a common characteristic that the accuracy of the sizing is greatly improved by quantity and reliability of the data provided. The responsible engineer should ensure that the most current flow rate and PVT data are given to the meter supplier to ensure rigorous sizing can be completed. Erosion may also influence sizing and should be addressed, if applicable. Sizing is initially used to determine the most appropriate meter from a standard range and then to determine how that meter performs over the measurement envelope. Sizing is fully detailed in API *MPMS* Ch. 20.3.

Determining the meter size required for an application as early as possible facilitates timely integration of the unit into the subsea architecture. The unit size and retrievability affects suitable locations, power and communication interfaces, tree and/or manifold layouts, and operational philosophies. The meter application and operational philosophy should be used to size the MPFM. If the MPFM is used for metering multiple wells the sizing data should include details for each well. Providing data for all wells in a field can enable interchangeability and a common spares program.

Sizing and performance should not be confused. Sizing relates to the determination of required meter turndown and the expected flow rates over the life of the meter. In addition, sizing can address the concern of erosion due to high flow rates and entrained particles. Meter performance relates to measurement accuracy and uncertainty (see 8.5). A correctly sized meter may not meet performance requirements due to a number of issues, see Table 1. However, a high performance meter may be incorrectly sized and not be able to measure across the full range of flow conditions. Sizing and performance should be considered together to ensure the most suitable meter is selected.

## 5.5 Performance

Flow meter performance is a broad subject which primarily considers meter uncertainty and is dealt with extensively in API *MPMS* Ch. 20.3. The complexity of multiphase flow measurement technology, flow regimes, and meter application means a performance strategy should be implemented. This section details the core considerations of

**Table 1—Considerations for Meter Performance Strategy**

| Item | Notes |
|---|---|
| Well trajectory/measurement envelope | — There is inherent uncertainty in the production profiles used to develop the well trajectory and measurement envelope. This can form an important aspect of overall uncertainty if the meter is expected to operate across multiple flow regimes.<br>— Clearly quantifying the expected ratios of liquid to gas can be used to set operational targets for sensors, and associated flow models and computations. |
| Sensor calibration | — Each sensor used in the flow parameter measurement has its own uncertainty, repeatability, inherent drift, and life expectancy.<br>— The fundamental measurement of flow parameters is effected by the combined limitation of the sensors and appropriate data are required to quantify both individual and collective contributions to uncertainty.<br>— The turndown of the sensors used in an application should be consistent with the projected well trajectory and operate across all the flow regimes encountered. |
| Meter location | — The orientation of the meter in the flow path may have an effect on the flow regime and hence the meters flow model. Some meters have a preferred installation orientation and an as-built reference should be considered as part of uncertainty.<br>— Adjacent discontinuities both upstream and downstream of the meter can create flow instability at the meter which may affect the meters flow model. The effects of installed geometries should be considered as part of uncertainty and differs from meter to meter. |
| Assumptions of flow model | — Meters typically use a flow model to determine the specific flow regime being measured. The flow models coupled with the actual measured flow parameters constitute a fundamental element of the phase computation. Interfaces between different flow regimes are not distinct and it is common for incorrect regimes to be used. The sensitivity of the calculation to regime selection is an important aspect of performance. Sometimes flow regimes are enforced through flow conditioning to match the expectation of a flow model. |
| Composition | — Fluid compositional factors such as salinity, conductivity, permittivity and viscosity can directly affect the usability of certain technologies. The variation in these parameters across the well trajectory should to be considered.<br>— Injected fluids like chemical inhibitors can affect the composition of the flow being measured and should be quantified as part of uncertainty.<br>— Commingling of fluids with distinct properties from wells or multiple completions / zones from the same well has a distinct influence on meter performance. Commingling plans should be defined and quantified for different mixing ratios. |
| Actual to standard conversion | — The phase behavior model used for conversion of gas and liquid volumes from actual to standard conditions should be suitable for the operational range of the meter. Most models show inconsistencies across their usable range and there are competing solutions including virial algorithms, modified cubic equations (Peng-Robinson), and multiparameter equations of state.<br>— As the fluid depressurizes the evolution of gas from the liquid phase should be accounted for properly. Similarly liquid drop out in wet gas system should be accounted for.<br>— Conversion should take into consideration the separation (multiple flash) processes from reservoir to sales point. |
| Software and communication | — Within the meter the software responsible for managing the calculation of flow rates should be qualified to ensure no computational errors are introduced. The uncertainty of software errors should be quantified across the entire operational range<br>— Due to the volume of data recorded by the meter, the uncertainty in transferring this information to the computational software should be considered. This software may not necessarily be local to the measurement system. Additionally, breakdowns in communication throughout the system generates inconsistent data for unsteady flows. |

such a strategy and should enable the user to create a management document. The document should capture application requirements, available flow data, required sizing data, determination of measurement uncertainty and a test plan that verifies all aspects of performance. Design validation and testing is covered in Section 8.

The first element of the meter performance strategy is a clear definition of application and this should be used to determine the uncertainty requirements. The application can be defined by a combination of regulatory, reservoir management, production management (e.g. flow assurance) and economic requirements. Additional design parameters might be required by specific applications that are not listed above. These may be determined by further consultation with other disciplines involved including flow assurance and reservoir engineering. This definition and uncertainty requirement should form the basis of all subsequent testing and have a dominant influence on commissioning and operational testing.

The quality of the design and configuration parameters affects meter performance. The manufacturer's functional specification, as detailed in 5.1, should provide comprehensive data on the key elements affecting uncertainty. The computation of individual phase flow rates typically involves the measurement of a series of flow parameters, a model used to determine the flow regime based on some flow characteristic (e.g. velocity), a detailed composition of the fluid being measured and an algorithm which uses these data in the determination of phase flow rates. The phase flow rates calculated are at operating temperature and pressure. Generally flow rates at standard temperature and pressure are required and therefore a final conversion is required. This conversion uses compressibility and saturation equations to establish the final oil, gas and water volume at standard temperature and pressure (STP). The functional specification should include relevant information on all aspects of flow calculation.

Each of the steps involved in flow measurement have either an inherent uncertainty or range of probable values. Overall evaluation of meter performance should consider both the quantifiable uncertainty of the equipment and the reliability of the system data. Further information on flow meter uncertainty is available in API *MPMS* Ch. 20.3. Where possible, further guidance should be sought on this specialist subject.

Performance testing is based upon the uncertainty requirements and aims to verify the meter's performance, over the full range of expected flows, see 8.5. Testing and field monitoring is an integral part of optimizing meter performance.

For any basic performance strategy the physical and system factors outlined in Table 1 should be considered and this should lead to comprehensive performance testing (see 8.5).

## 5.6 Mechanical Design

The supplier should ensure a comprehensive design file is available for the MPFM. Based on the design parameters detailed throughout Section 5 calculations should be completed for the following.

— Design life should be determined based on mechanical and electrical reliability studies including mean time between failure (MTBF) data on electronics, internal erosion due to typical operating conditions, fatigue or creep, internal and external corrosion, and sealing and connector integrity.

— Pressure containment calculations should be given which conform to standard API pressure ratings, based on acceptable materials for specific API material classes. This shall include factors of safety for hydrostatic pressure tests and nonstandard materials e.g. ceramic windows. Derating of pressure class should be identified where relevant.

— Hyperbaric pressure calculations should be based on internal pressure at atmospheric conditions required working depths and shall include safety factors for testing.

— The MPFM should be designed for API standard temperature ratings. This should include supporting calculations or qualification data for seals, sensors, controls, pressure containing materials, dynamic components, pressure balancing systems (contained fluids), and connectors used for retrieval components.

— Design documentation should include objective evidence that the design meets functional requirements under large changes in pressure and temperature, e.g. resistance to explosive decompression and creep.

— A cathodic protection study should indicate the required anode weight and placement required to ensure the calculated design life.

— The design should define storage conditions on land and sea including environmental temperatures, atmosphere, and vibration.

— Lifting and handling points should be reviewed for suitability based on project/integrator lifting plan.

## 5.7 Thermal Management and Insulation

The MPFM electronics shall conform to API 17F wherein subsea-installed equipment shall be designed, tested, operated, and stored in accordance with the temperature ratings listed in API 17F. This limits the extended operational temperature to 40 °C (104 °F) for subsea electronics as measured internally within any electronics housing. MPFMs are often insulated as part of the system flowline and production temperatures can exceed the given specification. MPFM electronics are not required to be insulated and should be designed such that heat transfer through the electrical containment housing is not detrimental to either the flowline or electronics themselves.

To ensure good thermal management the responsible engineer should ensure a full analysis is conducted of the MPFM control board and components using actual power dissipations. This should be used as part of the MTBF analysis recommended (see Section 7). Temperature monitoring for the internals of enclosures used for control boards should be available during onshore testing and offshore operation.

## 5.8 Subsea Architecture Interface

The MPFM interface is normally flanged or welded directly into the flowline depending on the fabrication of the structure. The specification of adjacent piping should be provided by the responsible engineer to the supplier including outside diameter, wall thickness, material grade, and specification, as well as any specific welding requirements. Welding on MPFMs risks damage to electrical components and should be done in consultation with the meter supplier.

Some meters include an independent flow line connector enabling them to be retrieved as a separate component, see 7.3 for retrievability. The supplier should provide all the appropriate dimensions and details for remotely operated vehicles (ROVs) or subsea tooling accessibility as well as support or auxiliary structures required.

Welding directly into the flow line can reduce the overall weight of the integrated component. Weight savings on a choke bridge are particularly advantageous.

Meters located on jumpers can be flanged in place to facilitate initial jumper installation and fabrication. Retrieval of some jumper geometries requires supplementary redesign and re-fabrication to account for pipeline/structure movement. Flanged meter interfaces simplify disassembly and reassembly in such cases.

Manifold or structure mounted units that are integrated directly into the flow line can be either welded or flanged in place depending on the fabrication philosophy for the individual structure. Meter retrievability becomes an issue when the assembly weight and size do not facilitate timely and economical retrieval (vessel availability and cost). See 7.3 for further details on intervention and retrieval considerations.

For meters where a sensor or communication pod is retrievable an interface funnel for guidance should be used. The receptacle and associated electrical connections should be integrated into the meter location and made accessible to either a ROV or running tool. Access to the pod should be considered as part of the meter location and the parent structure layout. In addition, electrical flying lead connections and paths should be considered when determining location of meter and accessibility.

Any MPFM component that is retrievable needs to have covers to protect the interface from debris or calcareous deposits for either long or short term, as required.

Electrical interfaces are covered in 5.9.2.

## 5.9 Electrical Connectivity

### 5.9.1 General

MPFMs require power and communications from the host facility. Power and communication can be provided using a variety of different philosophies; the most common ones include the following.

— Utilizing subsea control module (SCM) to provide power and communications to a dedicated MPFM. The MPFM should be compatible with the SCM and not exceed the communication bandwidth and power load. This option is generally used in new field developments since SCMs require provisions for the supply of MPFMs. This is generally achieved by including the MPFM as part of the subsea production control system and providing interface to the MPFM through the production tree or production manifold SCM. Operationally, the interface should have minimum interferences with the other production functions of the subsea control system. The required data transfer rates and SCM's power budget for the MPFMs should be considered as part of the Reliability Plan.

— Using a dedicated distribution module for distributing power and communications only to the MPFM is also a common practice. This method can be used for projects with limited capability on the SCMs to control the MPFMs, or for already producing fields which require the installation of MPFMs. This method of distribution may necessitate the use of dedicated copper conductor quads and fiber optic communications from the umbilical.

### 5.9.2 Connectors

Discrete electrical and optical connectors as well as hybrid connectors can be used for the provision of power and communication to MPFMs. Four pin copper connectors generally separate power and communications. The primary factor that governs the connector types used for MPFM power and communication is required/preferred data transfer rates. Connectors are typically pressure balanced wet-mateable electrical or optical connectors (rated for project design depth) and installable using an ROV.

Connectors from the supply (whether it be production SCM or dedicated MPFM supply) to the MPFM come in a variety of arrangements of pin numbers.

Some MPFM suppliers offer separate, multiple redundant power/communications systems with dedicated power and communication interfaces. In these cases, multiple connector interfaces may be required.

### 5.9.3 Power

The electrical power interface should be in accordance with API 17F power consumption categories and is typically project specific based on the MPFM power requirements, subsea infrastructure and electrical distribution capacity and limitation.

Meters and instruments have a range of power consumption requirement including; startup (inrush current), idle, back up monitor mode and primary monitor mode. All modes of operation have different power requirements. The system supplying the MPFM should be able to supply the highest demand without causing a drop in the system voltage below the MPFM voltage operational threshold.

A power interface specification from the meter supplier should fully detail requirements for power, voltage, current and frequency across all operating conditions of the meter. The operating conditions should include extreme or abnormal situations that may arise during field life or those created during a meter error or fault. An interconnection diagram should be provided to describe the electrical interfaces. Cabling and glands that are utilized should satisfy both the site hazardous area installation requirements and any additional requirements stated by the supplier.

MPFM power consumption requirements have a significant range between suppliers which can be an order of magnitude in difference. It is important to provide sufficient and constant power in accordance with the peak power consumption requirements of MPFMs.

Generally MPFMs require an input voltage from 20 V to 35 V.

#### 5.9.4 Communication

Data quantity and transfer rate is dependent on the meter application and supplier. Each supplier generally has a preferred communication interface and protocol to suit specific project requirements. A communication interface specification from the supplier should be provided. Required data transfer rates of a given project assists in ascertaining whether a specific communication method is sufficient, or if alternate communication methods should be proposed. Data transfer requirements of MPFM communications are primarily influenced by the quantity of data to be sent from the MPFM internal flow computer to the host facility.

In some cases, raw data transfer from the MPFM instrumentation to the host facility is required. This larger amount of data may require higher data transfer rates. Smaller data packets, for short measurement durations can be transferred over a longer period. The same considerations apply for uploading data to the meter.

Current communication interfaces and protocols for MPFMs are as follows:

— Canbus/Can Open (moderate data transfer rate);

— Modbus (RS-232 or RS-485) (moderate data transfer rate);

— Ethernet on copper (TCP/IP) (moderate/high data transfer rate);

— Fiber Optic (high data transfer rate).

Further reference should be made to API 17F for subsea control monitoring systems.

#### 5.9.5 Software and Data Content

MPFMs suppliers have an operator interface software for all meter instruments which provide monitoring and analysis. This software typically gives the operator any level of information required from the MPFM. The software is usually designed to work with singular or multiple meters, sensors and gauges and combines the instrument software with specialized flow assurance and production optimization software. The goal of each supplier's software package is to give the operator access to the flow information/conditions. Supplier software generally comes with a series of specialized packages in the areas of flow assurance, erosion, corrosion, simulation and production control, and virtual metering. MPFM software packages enable operators to access everything from individual data series corresponding to a single instrument to providing complex guidance for choke settings. The software also quickly compiles data in order to identify trends and areas which may require further analysis.

MPFM software includes an operator interface and data management software for ensuring safe and reliable operations. It can be modular or all-inclusive.

Data servers generally reside on the host facility and gather, store and distribute data from subsea meters, sensors and gauges. Data are stored in a data format that is specifically designed for handling large data volumes with high performance. An interface is generally provided to enable the data server to communicate with each MPFM. The operator interface usually resides on the host facility. This may be incorporated into the production control system human machine interface and serve as a standalone system. The operator interface application is designed for product-specific functionality that provides all the required graphics, algorithms and data handling functions for an MPFM.

## 5.10 Electrical Enclosure and Printed Circuit Board (PCB)

Each MPFM includes PCBs, which provide the following functions:

— receive power/communication supply power from a subsea control system;

— provide electrical power to all other components in the MPFM;

— acquire data from all transmitters and the gamma detector, if applicable;

— calculate flow rates and other measurement values;

— communicate the measured values to a supervisory control and data acquisition (SCADA) system, process control system, or a service manager computer, via a communication link to host facility;

— diagnostic measurements of itself and other system components.

The PCBs are housed in an electronic enclosure whose design may vary depending on supplier and project requirements. Enclosures can have dual redundant electronics or single electronic compositions and can be retrievable or non-retrievable. The enclosure principally provides containment for the electronics/PCBs (benign environment), structural integrity for water depth, a foundation for electrical feed through and heat transfer.

## 5.11 Labeling and Marking

Product labeling and marking should be per API 6A. The following information should be made visible on the MPFM using a process suited to subsea environmental conditions:

— project name,

— project tag number,

— supplier name and address,

— design code,

— temperature rating,

— rated working pressure,

— maximum test pressure,

— nominal bore (for connecting piping),

— weight,

— serial number,

— purchase order number or similar reference,

— part number,

— communication protocol,

— IP address/Modbus slave address.

The flow direction should be clearly marked for fabrication and installation. Lift points on the meter should be clearly marked. Interface alignment and full engagement reference markings should be included where applicable. Appropriate colors should be used to ensure maximum visibility for ROVs interfaces (see API 17A). The manufacturer's product size and reference should be included if not indicated as part of the serial number.

MPFMs that use radioactive sources for measurement shall comply with all regional requirements for identification and warnings.

NOTE These are covered in ISO 21482 (Ionizing-radiation warning), ISO 7205 (Radionuclide gauges), and ISO 2919 (Radiological protection, Sealed radioactive sources, General requirements and classification) for the various different radioactive categories. The radioactive labels are in accordance with ISO 361 (Basic ionizing radiation symbol) and IAEA TS-R-1 (Regulations for the Safe Transport of Radioactive Material), unless ISO 21482 (Ionizing-radiation warning—Supplementary symbol) and ANSI N14.7-2013 (Radioactive Materials: Guidance for Packaging Type A—Quantities of Radioactive Materials) are more stringent.

## 5.12 Additional Equipment

### 5.12.1 Service Computer

The purpose of a service computer is to confirm the full and correct operation of an MPFM during all stages of delivery. As such the service computer should be a portable test device designed to be easily transported. The computer shall have the correct and latest revision of the supplier communication software.

Connection from service computer to MPFM is typically through an electrical test unit (ETU). Both power and communication requirements during testing should replicate those seen in subsea operation. The ETU should provide suitable power and communication conversions, as well as being rated for MPFM start-up conditions and any specific project requirements.

Since the service computer is used throughout flow meter delivery, it should be of rugged construction appropriate for shipping, storage, handling at fabricator sites and offshore.

### 5.12.2 MPFM Simulator

Simulators are required for system integration for power and communication when the actual meter may not be available. Simulators should replicate the correct power and communication behavior of the meter being delivered.

This is achieved by:

— ensuring the same or equivalent simulated instruments with the actual flow computer present in the MPFM are used;

— power load, communication, and accessibility is the same as the MPFM;

— reproducing the inrush and continuous power consumption of the MPFM;

— duplicating the full range of operating conditions and output data to the SCM.

Gamma ray sources can be replaced with devices giving similar functionalities and loads.

# 6 Radiation Based Devices

## 6.1 General

In addition to the design requirements outlined in 5.3, meters with radiation based devices should conform to the following.

— Use a suitable housing compliant to recognized industrial nuclear design and proven for subsea modification, see additional references in the Bibliography.

— Meter design and performance should include decline in radiation source intensity as part of design life.

— Use all appropriate markings and labels meeting international and local regulations during shipping, handling, and fabrication.

— Ensure enclosure is designed to prohibit personnel from direct exposure to source.

— Be suitable for remaining in place for entire design life even if not in service.

## 6.2 Transportation and Importation

It is crucial that the meter supplier and operator review the requirements for shipping MPFMs especially in regards to the radioactive materials utilized. All MPFM suppliers should clearly outline the handling requirements for their products, as well as address the logistical complications that a specific project may encounter. Many countries require that equipment comply with maximum radiation exposure levels, set by a nuclear regulatory body, in order to import the meter systems. In addition, there are also registration requirements that each host country's government may require for importation and installation.

The operator's radiation safety officer (RSO) should be involved from the initial stages of meter specification to ensure all regulatory and documentation requirements are met.

## 6.3 Repair

Retrieval of a meter with a radioactive source should include the requirement for a supplier representative on site. The supplier is responsible for ensuring the integrity of the housing of the radioactive source. Movement of a source from any location requires consultation with the RSO who is required to maintain information regarding all radioactive source locations.

Precautions should also be considered in regards to registration and transportation should a unit be required to ship internationally for repair at the original suppliers location.

## 6.4 Decommissioning

Decommissioning of radioactive devices shall be managed by the supplier in cooperation with the operator's RSO and local and/or government regulations. Radioactive devices shall be returned to the original equipment manufacturer or according to local and / or regulations.

# 7 Reliability

## 7.1 General

Reliability as a complete subject is outside the scope of this document. For detailed information on reliability reference should be made to API 17N and applicable operator requirements.

Reliability should be managed by the supplier using a reliability plan which ensures maximum meter availability. A reliability plan encompasses all aspects of meter development, analysis, qualification, testing and operation, see Figure 1 for a graphical representation. The plan should detail the applicable reliability and risk analysis tools used at each stage of meter life. Multiple sections of this recommendation should appear under the scope of a robust plan. Due to the nature of MPFM service the reliability goal should be to maximize availability. Note that availability requirements defined by the operator should be realistic and achievable and are more appropriate when considered as part of an overall field operational plan. Primary consideration should be given to early life failure wherein a suitable qualification program can replicate component failure. Full design life availability may require extrapolation from test results or statistical data and should focus on proven engineering solutions, high component specification, sub-supplier management, good manufacturing standards, and accurate quantitative data.

An outline of a suitable reliability plan is given below.

— **Reliability Strategy**: The plan should start with a clear specification of meter reliability requirements including specification for availability, MTBF, mean time to failure (MTTF), mean time to repair (MTTR), and maintainability goals (cost and time). The strategy should outline the methodology for achieving and proving the reliability goals. The reliability plan should endeavor to communicate the difference between achievable, determinable availability and stretch goals required by industry.

— **Design File**: The design file, as outlined in 5.6, should not only address the mechanical design of the meter but also present calculations related to design life. Design life calculations may include fatigue and thermal analysis, material degradation (elastomers), corrosion, erosion controls board component life, sensor drift, radioactive source half-life, and all other aspects of the meter that can be reviewed from a theoretical perspective. Design for availability is initiated during the design phase which the design file documents. Requirements for meter components are most often derived from this document and may have the greatest impact on availability. The reliability plan should identify the primary elements of the design file which have the greatest impact on availability and where they are incorporated into the reliability strategy.

— **Failure modes, effects, and criticality analysis (FMECA)**: Design validation is outlined in Section 8, which includes summary FMECA requirements. In respect to the reliability plan, the FMECA should translate the design file concept into a series of potential failures based on operational modes. This identifies key components within the design that directly affect availability. The mitigating actions associated with these modes generally involve higher component specification and inspection. Unquantifiable component interactions or unknown consequences are best determined through extended qualification and life testing. The mitigating actions (redesign, component specification, redundancy, and qualification) that directly relate to resolving the identified failure modes are key elements of the Reliability Strategy. The use of redundant systems is further addressed in 7.2.

— **System Analysis**: In addition to a FMECA, a number of specific reliability tools can be used to assess the meter design including risk categorization and fault tree analysis. A system analysis should involve the entire process involved in specifying, purchasing, assembling, factory acceptance testing, integrating the meter into a subsea structure, commissioning, and operation of the meter throughout its life. Sub-supplier reliability is integral to overall meter availability and probably most associated with early life failure. A reliability assurance plan considers the system aspects of the meter and typically covers sub-supplier management, design for manufacture, and supply chain management. It is used in addition to a reliability plan to ensure consistent delivery of a reliable product.

— **Qualification**: General qualification testing is outlined in 8.3. Certain qualification tests are unique to the meter design as a product of both design file and FMECA. A comprehensive qualification plan should be aimed at increasing availability through identifying unknown system failures under operating conditions or by acquiring statistical data on component life through extended testing. Operational conditions should replicate design file specifications as well as short term extreme conditions that may occur throughout the life of the meter. Qualification testing should provide comprehensive data in establishing early life availability. Extended tests should assist in design life calculation and any data extrapolation should be identified and the rationale given.

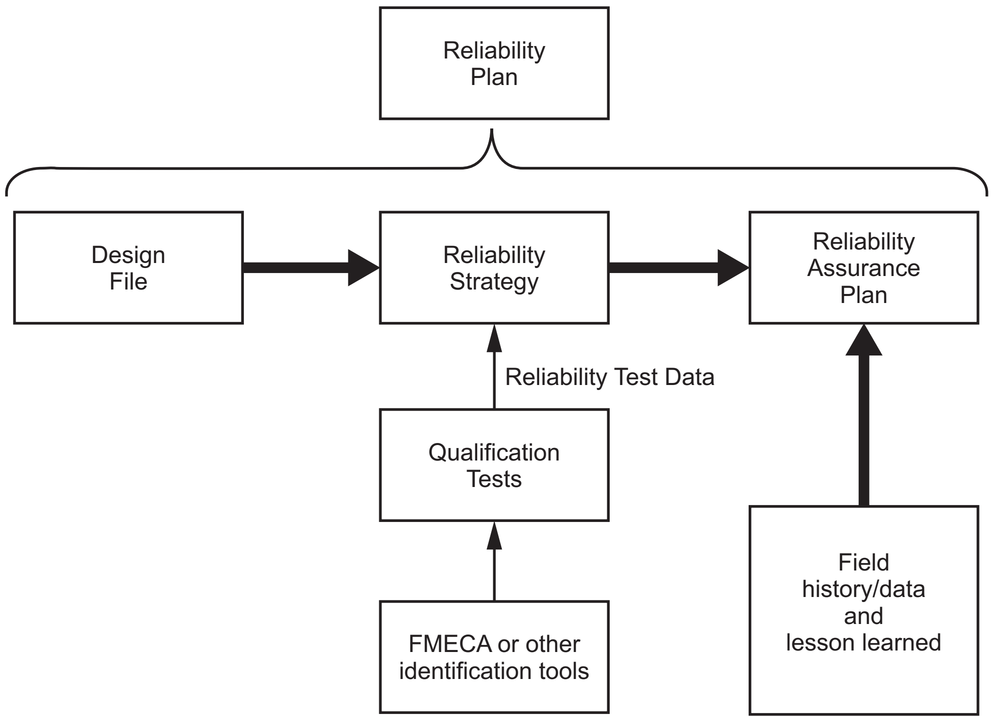


**Figure 1—Reliability Plan Overview**

— **Operation**: The reliability plan should be maintained and updated with relevant operational data covering operating parameters, failures and lessons learned. A meaningful plan should show continuous monitoring, improvement and determination of availability. Any changes to the meter design should go through the same cycle of assessment and review as the original design with communication to the operator as to the increased availability achieved.

Within the reliability plan particular attention should be given to both the control system and the meter software. Suitable processes, based on a recognized standard, should be established by the supplier for finding defects in the software and ascertaining their effects on availability. Updates and revisions to software should undergo a similar review. The software should be sufficiently user friendly to ensure incorrect inputs and operations are managed at applicable user levels. It should also apply good housekeeping practices to continuously monitor, self-diagnose, and prevent run-time errors and to quickly recover from transient hardware faults. Software qualification is further addressed in 8.3.5.

In addition to availability the supplier should ensure the reliability plan address maintainability including the cost and duration for replacement parts, refurbishment and repairs. This is particularly important when fields are located in areas with strict controls on radioactive sources or where no supplier base is located.

## 7.2 Redundancy

Redundancy is the duplication of critical components or functions of a system to increase availability. A reliability plan should be used to identify the essential elements affecting meter functionality, their life expectancy, and the associated failure modes. Meter operation may be extended by using distinct and separate parts that duplicate the purpose of the original failed component. The duplicate part should function exclusively from the original element to ensure that the same failure mode is not repeated. Redundant elements that are used to extend operational life and that do not operate until required, should be designed for long periods of inactivity.

Redundancy can also be achieved by replicating functionality. For an MPFM, any alternate means of ascertaining pressure, temperature, velocity, density, void faction, or other measurement component should demonstrate similar accuracy, repeatability, and uncertainty as the primary means.

If measurement redundancy, whether by component or functionality, reduces meter performance this should be highlighted by the manufacturer. Compromising on performance for continued functionality is often desirable in the short term for certain applications. Flow assurance applications where tracking is a primary parameter may be able to operate for extended periods with reduced performance. Fiscal transfer applications generally require consistent performance with no acceptance of loss of accuracy. Intervention plans for the meter can be combined with planned maintenance or shutdowns if decreased performance is unacceptable.

Typical meter elements that have redundant components include differential pressure (DP) transmitters, pressure transmitters, and temperature sensors. Other subsystems that should be considered as part of any reliability study for redundancy should include; major sealing groups, electrical connections, mechanical connectors, PCBs for data acquisition and control, and detectors.

## 7.3 Retrievability

MPFM retrieval strategies are based on either recovering the entire meter, supporting structure (choke bridge or jumper), or a pod containing critical elements most prone to malfunction or those requiring maintenance. The retrieval design philosophy should ensure that the most complex component/connection is removed in its entirety with the fixed (non-retrievable) element being as simple as possible. When a pod is the sole recoverable element of a meter extensive testing should be performed to determine the reliability of the remaining elements.

Pods typically contain electronics, transmitters, and sensors that are part of measurement and are prone to drift, degradation, or failure (pressure transmitters, temperature sensors, humidity sensors, etc.). Recovery of radioactive elements requires supplier assistance, see Section 6.

The retrieval plan for each field and meter application is influenced by operator best practice and a number of unquantifiable elements including geographical location, field history, field life and field design.

The location and application of the meter can influence the overall approach to retrieval. When defining a Retrieval Plan the following elements should be considered.

— Remote software update: Can the meter software be updated remotely to resolve the issue.

— Supporting structure: If the meter is integrated into a retrievable structure, the size, shape, weight, and connection system of that element dominates the retrieval strategy.

— Application: Does meter failure require immediate removal or are there system controls and redundancy that can be utilized.

— Location: Does a failure at the meter location require a system shutdown for retrieval and ceasing production? Does the MPFM have a bypass line?

— Reliability Plan: Is the reliability plan enough to demonstrate the life expectancy of the meter under normal and extreme operating conditions?

— Support vessel: Does the location necessitate the use of a large vessel for retrieval of an integrated component (jumper, choke bridge)? Can a smaller vessel be used for retrieval and replacement of controls pods? Are periodic interventions required as part of the field design and are vessels continuously available for support? Can system design be used to continue production until that intervention?

— Spares: Are replacement meters and/or pods available? For meters using gamma sources are spares available in country and if not are significant customs/delivery durations expected?

— Safety: Retrieval of large subsea elements create concerns associated with securing, lifting, and manipulation. Any retrieval strategy should consider the overall relative safety of a proposed recovery plan.

— Cost analysis: Once information concerning all the elements above has been gathered a cost analysis for a number of options should be produced to determine if there is any significant economic advantage of a particular retrieval strategy.

If the meter is integrated into a retrievable assembly the connection and seal of that element should become part of the meter reliability plan.

A drop object analysis should be conducted on the meter location once the retrieval strategy has been complete. Adequate protection should be provided to ensure critical elements of the meter and flow line are shielded against items unintentionally released during operations in and around the meter. Protection should consider deflection of any item as part of the shielding design.

# 8 Test Requirements and Recommendations

## 8.1 General

An MPFM requires a number of tests throughout its life cycle. Initial tests should be used to verify meter design. Production tests should be used to prove manufacturing integrity and consistency. Performance tests should be used to validate the suitability of the meter for a specific application. Finally, in situ commissioning and operational tests are required.

Due to the differences in meter technology and applications there is no standard set of tests that can be used. A meter test plan should be developed which is concurrent firstly with measurement principle, then required performance and finally optimized for operational use.

This section details suitable technology qualification methodologies and continues providing requirements and considerations for the performance strategy. A series of shared tests that are required for all meters to verify mechanical integrity is also given.

## 8.2 Design Validation

Design validation is the establishment of documented evidence to provide a high degree of assurance that a specific system, process, or facility consistently produces a product meeting its predetermined specifications and quality attributes. Evidence is generally produced by completing a series of relevant and representative tests or by developing accurate computational models which simulate functional parameters. This information is typically contained in a series of documents including the design file, the functional specification, the qualification plan, and the qualification results.

Qualification testing is part of design validation process. The intent of qualification testing is to prove that the design meets the specified design criterion.

NOTE The validation process is addressed in 8.2. Some commonly recommended testing used as part of verification is addressed in 8.3. Due to the difference in meter technologies not all tests are detailed. DNV RP A203 provides a suitable guide for equipment qualification.

It is expected that all MPFMs designs adhere to a proven engineering process. Design validation requires the confirmation that documented evidence exists that provides a high degree of assurance that the meter consistently meets its predetermined specifications and quality attributes. A design file, as outlined in 5.6, should exist that documents a meter specification with supporting calculations for pressure containment, material compatibility, meter performance, reliability/field life, and meter lockdown mechanism based on operating and environmental conditions.

The meter functional specification, required as part of the performance strategy, can be used to provide relevant manufacturer details on the design of the relevant aspects of performance. These should include the intended relationship between sensor functionality and flow model versus expected performance. This proves that the measurement technology is capable of achieving a specific uncertainty for a particular flow regime based on reliable process information.

A qualification plan linked to the design file and functional specification should provide physical assurances that the meter can achieve predetermined acceptance criteria. DNV RP A203 details a suitable process for technology qualification. API 6A details a number of tests used for oil field equipment that can be used as a reference guide (it is not specific to metering technology). As a minimum the qualification plan should aim to verify the primary calculations presented in the design file and supply sufficient reliability test data to confirm the design life and availability. The following contents would be anticipated in a thorough qualification plan.

- Specification of meter with description of operating principle (see 5.1).
- Definition of key functional tests including:
  - pressure containment,
  - environmental operation at temperature and pressure,
  - mechanical functionality for lockdowns and connectors,
  - communication transfer rates and integrity,
  - power requirements,
  - software processing,
  - measurement calculation and thus requirements from measuring sensors and relating their performance to uncertainty.
- Determination of required reliability data to confirm operational life.
- Assessment of meter technology for failure modes (failure mode and effects analysis [FMEA]).
- Test proposals for:
  - qualification tests,
  - collection of reliability data,
  - failure modes.
- Definition of acceptance criteria and continuous performance measurement.
- Test results.
- Standardized tests for manufacturing (what is required to confirm design for each assembly).

The plan should conclude with a recommendation for a factory acceptance test (FAT) program that is required to verify key requirements for each meter. An outline FAT plan is given in 8.4 with minimum acceptance criteria.

A number of qualification tests that are expected as a minimum for a MFPM are detailed in 8.3. It is expected that a number of additional tests is required to satisfy meter performance, reliability, and design life calculations. It is recommended that the application and project requirements of the meter be used to determine all appropriate tests and acceptance levels. Tests that are required as part of the performance strategy are outlined in 5.5.

## 8.3 Qualification Testing

### 8.3.1 General

The qualification tests outlined in this section are expected as a minimum. Extended performance tests, accelerated life tests, highly accelerated life tests, highly accelerated stress screening, environmental tests (temperature and pressure cycling), and tests for specific metering technologies are typically required by operators, in addition to testing outlined herein.

A comprehensive qualification plan should provide sufficient data over an extended test period to support determination of early life availability. Testing should be completed at both a component and system level to ensure the consequences of complex interactions are well understood. Extrapolation and interpolation of test data can be sufficiently justified with established mathematical methodologies.

### 8.3.2 Pressure and Temperature Rating Qualification

The meter shall be qualified to the test requirements of API 6A. The minimum and maximum pressure and temperature ratings shall be per API 6A. The standard rated pressure and standard rated temperature of the specified equipment shall be used for the test. Standard pressure and temperature ratings facilitate safety and interchangeability of equipment. Nonstandard pressure ratings are out of scope of this recommendation.

Any scaling used shall be in accordance with API 6A. Where MPFM size scales do not affect seal areas in bore penetrators or other primary seals, scaling may be used across a wider range of meters. Scaling cannot be used if a primary seal's nominal size increases two sizes. Nominal sizes are given in Table F.3 of API 6A.

### 8.3.3 Hyperbaric Qualification

Hyperbaric testing shall be per API 17D. The test pressures shall be at 1.1 times the maximum operational water depths and should conform to temperature requirements. Meters that have no moving components shall be treated as static systems and shall adhere to the pressure cycling requirements of API 17D.

### 8.3.4 Electronic Systems Qualification

API 17F details the requirements for electrical stress screening and guidelines on the electromagnetic environment for subsea components respectively.

All MPFMs shall be qualified to API 17F. Additional tests determined from API 17F shall be in accordance with Type 1 or 2 Location Classes as determined in the manufacturers design file.

All electronics shall be tested to IEC-6100-4 for electromagnetic compatibility.

### 8.3.5 Software Qualification

Software for MPFMs should be designed and qualified in accordance with a proven international standard or practice. Multiple supplier specific standards exist and the responsible engineer should ensure that the most suitable and rigorous is applied.

ISO/IEC 25010:2011 may be used for the evaluation of software quality. In the standard, quality is defined using a set of characteristics including; functionality, reliability, usability, maintainability and portability. Some of these characteristics have direct impact on the user and others on the manufacturer. For a robust measurement system the software functionality should consider the following attributes; suitability, accuracy and interoperability. Reliability attributes include; maturity, fault tolerance, recoverability and reliability compliance. Usability should consider understandability, learnability, operability, and usability compliance.

An attribute is an entity which can be verified or measured in the software product. Attributes are not defined in the standard, since they vary between different software products. The standard provides a framework for manufacturers to define a quality model for meter software. The framework and plan is unique to the manufacturer and focuses on their specific concerns.

## 8.4 Factory Acceptance Testing

### 8.4.1 General

FAT tests should be derived from the manufacturers design file and qualification report. The qualification process proves that a design can function as intended throughout its operational range. The intent of FAT is to verify the integrity and consistency of the manufacturing process to ensure each individual meter meets the standards of the qualification unit. Guidance on standard tests is found in 8.4.2 through 8.4.7.

Additional project or customer specific testing should be covered in an extended factory acceptance test (EFAT).

An expanded section on meter performance testing is addressed in 8.5, which is required as part of the performance strategy.

### 8.4.2 Hydrostatic Pressure Test

Depending on meter application and location API 17D, production specification level (PSL) requirements may apply. It is recommended that PSL requirements be applied where possible. This shall typically require two hydrostatic tests of 3 to 15 minutes hold duration at 1.5 times maximum working pressure, per API 17D. In addition, a gas test may be required (see 8.4.3). All meters shall conform to API 17D if part of an applicable assembly.

As the meter becomes part of the production system or flow line assembly it should as a minimum be tested to the same or more onerous standards. The meter shall be tested as a full assembly prior to incorporation into the system.

The meter undergoes multiple hydrostatic tests depending on location. This can include but may not be limited to manufacturer tests, full assembly tests (tree, jumper, manifold), and field commissioning tests (flow line commissioning).

### 8.4.3 Gas Pressure Test

Gas tests shall apply to PSL 3G assemblies per API 17D. The referenced section is written specifically for valves and chokes but can be applied to MPFM where actuation of moving part can be disregarded.

### 8.4.4 Hyperbaric Pressure Test

Hyperbaric pressure tests shall be conducted on each assembly per API 17D with acceptance criteria given in API 6A. Qualification tests shall prove the operational limit of the design to 1.1 times required ambient pressure. External pressure requirements for individual projects shall be per the project philosophy.

This may require the meter to be tested to actual water depth or retested to qualified depth. It is recommended that the more onerous requirement be implemented where possible and that standard procedures be used if in existence.

#### 8.4.5 Helium Leak Test

All electrical enclosures should be helium leak tested. There are a number of helium leak test procedures that can be used and they are dependent on the design of the electrical enclosure. Leak tests may be conducted at several points in the manufacturing process.

Acceptance criteria should be zero bubbles during a 15 minute pressure hold period.

#### 8.4.6 Electrical Stress Screening (ESS)

All electronics shall be tested per API 17F at a component level. ESS is designed to reveal failures due to manufacturing non-conformances and substandard components. Further tests may be required at subassembly and final assembly level. Additional tests can be designed to identify the specific defects associated with the level of assembly.

The minimum acceptance criterion for ESS testing of meter controls includes no errors during continuous function monitoring and no significant physical damage.

#### 8.4.7 Inspection and Functional Test

The FAT should include full functionality testing of all instrumentation, the flow computer and communication to a service computer. This includes testing of software as well as hardware. The FAT should include, but not be limited to, the following activities.

— Equipment visual inspection.

— Power-up test of the whole system.

— MPFM boot test.

— MPFM electronic redundancy test (consists of turning each redundant electronic off while verifying communication with transmitters).

— Electrical continuity test and insulation resistance test.

— Current consumption test.

— Instrumentation tests (testing of all internal instrumentation including internal diagnostic sensors).

— Surface radiation test.

— User interface/parameter check.

— Verification of the software version and software image installed on the MPFM meter is according to the MPFM specific software report for the meter. If any deviations are observed on the software version or software configuration on the meter versus the software report, this needs to be approved by the supplier. In addition, all old software versions should be deleted from the meter. A software upgrade test should be performed prior to the flow test, if a flow test is applicable. This test shall be done using a software update application. In this test, a software upgrade is demonstrated. An old version is downloaded to the meter, and the upgrade is demonstrated.

Power and communication should be tested during the commissioning process to ensure the integrity of the installation (see Section 9). Complete MPFM set up should be performed including; instrumentation readings review, zero trim of required transmitters, and baseline reference recordings. Normally there is no process flow during the commissioning phase.

#### 8.4.8 Final Inspection

A final inspection process should be used by the supplier to ensure all meter documentation is correct and representative of the unit being shipped. Documentation required for the meter delivery typically includes but is not limited to all signed inspection documents, accepted nonconformance reports, signed and completed FAT and EFAT test procedures, installation instructions and handling and storage documents.

Before shipping all serial numbers and identifying labels shall be verified and notated on a suitable protective packaging for the meter. The shipping container should be suitable for sea freight and long term storage and have displayed all relevant identifying markings as required by local authorities. The required shipping documentation should be validated.

### 8.5 Performance Tests

#### 8.5.1 General

Performance tests are required to verify the ability of the meter to meet the requirements of the application based on reliable process data. Performance tests are an inherent part of qualification, FAT and extended third party tests required by operator. Uncertainty can be calculated according to API *MPMS* Ch. 20.3. Verification of uncertainty is a requirement of performance testing. Specific flow tests required for calibration as part of FAT should be specified by the supplier. A calibration procedure should be available from the supplier to ensure that meter is correctly configured during system integration and commissioning.

Due to the complexity of replicating all the variables in a multiphase flow application there are currently limited full scale test facilities. A full scale facility would be able to reproduce all suitable flow regimes for various gas-oil ratios (GORs) for different hydrocarbon compositions, at operating temperature and pressure across a number of operational cases. In essence a full test facility would be able to replicate the actual application the meter is intended for. Testing is generally accomplished by segmenting specific elements of measurement and verifying that the equipment can operate for that specific condition. Regime testing may be accomplished by using air/water mixtures at standard temperature and pressure. Actual hydrocarbons may only be tested across a limited range for a particular composition at a site that may only facilitate low pressure tests. In situ tests can be used as part of meter commissioning and a limited number of points may be used to validate earlier assumptions used as part of factory testing.

The performance strategy should maximize the available test facilities including the manufacturer's in-house capabilities, third-party specialist test centers and commissioning/in situ test programs. The cost of performance testing should be justified by the criticality of the meter application

#### 8.5.2 Functionality Tests

Functional testing should occur during FAT or EFAT. API *MPMS* Ch. 20.3 details comprehensive recommendations for meter calibration, correction, performance testing and verification. The scope of testing is to ensure that all sensors, transmitters, receivers, software and communications are functioning within the given range of the meters functional specification. Before performance testing can start each component in the uncertainty calculation has to be proven to be operating within specified limits.

Sensor functional testing usually includes:

— pressure and temperature measurement devices;

— DP measurement devices;

— gamma ray instruments/densitometers;

— electrical properties sensors, such as capacitance, conductance, and microwave systems.

Functional testing does not account for drift or long term maintenance. This should be included as part of any operational plan.

Power, communication, and software functional testing should be detailed as part of the qualification program. As few changes occur in the resultant system after original qualification, functional checks should be used to ensure post ESS operation and that project specific software inputs are correct.

#### 8.5.3 Static and Flow Loop Tests

Meter readings taken under no-flow conditions using fluids with known properties are useful measurements in calibrating MPFMs. Empty, water-filled, and oil-filled pipe are good examples of such measurements. If the baseline parameters for these conditions are logged first at factory calibration, later at field commissioning, and at regular intervals thereafter, one can use trends to distinguish between random deviations of the measurement versus a systematic drift.

A static meter correction is sometimes used to describe the activity of installing the device in a multiphase flow loop, recording the meter's zero flow performance, and possibly adjusting certain parameters. API *MPMS* Ch. 20.3 details recommendations for meter verification at a reference facility.

The primary aim of flow loop testing is to quantify the meter uncertainty by measuring the various flow regimes encountered in the well trajectory with some consideration for the potential fluid compositions. The test essentially encompasses the complex elements of measurement technology, equipment calibration, and the effects of process data and sensitivity of flow model to regime change. Assuming the conditions can be fixed it is the most suitable test for direct comparisons between meters.

Flow loops all have their own unique design but should include an independent separation and measurement system with greater accuracy than the MPFM. Meter proving rigs are recommended to be more accurate than the system undergoing measurement but may have a reduced turndown or range. Inconsistencies between independent test laboratories measurement techniques and the meter should be addressed prior to any tests. API *MPMS* Ch. 20.3 further details requirements for flow loop testing.

Capabilities at manufacturers and third party test houses vary widely. Typically flow loops either use air/nitrogen/water/oil mixtures to simulate a wide variety of flow regimes or real hydrocarbons (dead crude and methane mix) at pressure representing a very limited range of flow regimes but potential compositions. If the application requires it, both facilities should be used as part of the overall performance strategy.

Air/water test facilities should be designed independently of the flow meter technology with separate proven rationales for determining flow regime and phase flow rate. It is more important that the rig be able to test across a range of regimes than continuously in a specific range. While the boundaries for flow regimes are affected by composition, pressure, temperature, and geometry the ability of the meter flow model to account for this in a representative flow like air/nitrogen/water/oil is indicative of its suitability for hydrocarbons. A reduced number of additional tests on a real hydrocarbon may then be possible to give appropriate confidence in the meters model.

### 8.6 Integration and Installation Assurance

Integration and installation assurance starts when a fully functional meter has left the supplier and ends once it is deployed subsea. Once the meter has left the control of the supplier it requires additional coordination by the responsible engineer to ensure correct integration into the system. This section details meter storage, fabrication into the subsea system (assembly as part of jumper, tree or manifold), site integration testing and verification up to installation. Meter commissioning is covered in Section 9.

It is recommended that an integration and installation assurance plan is created by the responsible engineer with the meter supplier. This should consist of multiple documents detailing best practice and support requirements for all activities identified. As some meters use radioactive sources there may be a number of additional shipping restrictions and documentation requirements. The operator should seek assistance from the equipment supplier in structuring an integration and installation assurance plan since they are required to ensure integrity at multiple points. The following elements outline the typical steps involved in deploying the meter and should be controlled by a suitable plan.

— Leave Supplier. The meter leaves supplier with all appropriate project documentation including FAT, EFAT, and integration instructions. The receiver/operator is now responsible for the meter. Additional hook-up and function testing may be required at numerous points throughout integration and installation.

— Receiver/operator needs to ensure all appropriate shipping documentation is in place. Certain documentation for goods receipt shall be completed by the receiver. For meters with radioactive sources, certain procedures and documentation should be completed. Meter suppliers typically give the operator detailed information on what is required. Special shipping requirements should be established early in the project so delays do not occur. The user has a company RSO whose responsibilities include tracking where each source is for the company. General awareness training is typically available from suppliers. It is best to work with suppliers to determine the requirements from the different governments and local authorities.

— When meters are in transit, damage can occur from shock and vibration. Shock and vibration monitoring should be used as part of the shipping container or on the ECM of the meter. Suppliers should set acceptable criteria for their meter and confirm measurements as part of the receive inspection test (RIT). RIT is generally used after long transit times or when extended yard storage is required.

— Third-party testing at flow facilities may be required as part of meter performance testing. Supplier support may not be required during testing. However support for lifting, connecting and confirming meter integrity on arrival and departure is recommended.

— As MPFMs are integrated into the subsea system as part of an assembly (tree, manifold or jumper) the meter supplier should be present. The integrator is responsible for assembly of the meter into the system but may also be responsible for system integration test (SIT) and other system testing. It is recommended that the meter supplier be present during this period to ensure the following.

  — Early simulator integration with control system whether on tree or manifold is conducted.

  — Correct lifting and handling of actual meter. Some awkward meter locations may require detailed handling, lifting, and fit-up plans prior to welding.

  — If welding on meter is required, it should be witnessed by the meter supplier. Meters can also be connected into the system by flanges. A communication check should be conducted prior to and post welding. Instruction for grounding electronics should to be followed during welding. High arc ignition welding is likely to damage electronics if grounding instructions are not followed.

  — Once integrated into the assembly, a hydrostatic pressure test of the assembly is required. As the meter should have previously passed a hydrostatic pressure test, this additional test confirms the reliability of the weld or the flange seal/gasket.

  — During further testing of the complete assembly (e.g. SIT) the meter needs to be used instead of the simulator. If possible, the supplier should conduct some measurement checking on sensors (at pressure or in empty pipe).

  — A supplier acceptance checklist should be provided that confirms meter functionality before shipping to installation or storage.

— Meter suppliers best practice for storage should be implemented on the assembly if required. Note that best practice can be region specific, i.e. drainage, shade, temperature controlled, covered, etc. Long term storage and recommissioning plans should include operation tests and checks.

— Dock test and deck tests should be conducted through SCM, if possible. Note that in some meter locations, an SCM may not be available.

— Section 9 details elements of commissioning that are used once the meter and assembly is installed.

— Retrieval of meters for failures or maintenance should involve the original equipment manufacturer. Meters using radioactive sources need to be tested on retrieval for radiant leakage. The user RSO should be informed of any retrieval of such devices (see Section 6).

— The decommissioning of radioactive type meters requires the presence of the original equipment manufacturer. At the end of field life, the radioactive source needs to go back to supplier.

Various checks should be conducted to ensure the meter is still operational and communicating. The safe and timely delivery of meters is best achieved using a preplanned logistics strategy coordinated in cooperation with the supplier. Figure 2 details the process flow for a typical integration and installation assurance plan.

# 9 Commissioning

## 9.1 General

Meter commissioning may require a cross-disciplinary team. This RP is limited to equipment specification, testing and qualification. The full scope of meter commissioning may require additional operational procedures to be implemented. While the scope of this section is limited to equipment configuration and the commissioning process a number of operational tasks are outlined that could be implemented as part of the cross-disciplinary approach. Ensuring meter performance is a long term duty that continues after commissioning.

Note that some of the tasks described in this section may be split between pre-commissioning and commissioning depending on the operators definition. For consistency all activities described herein start after meter installation and subsea system connection to support facility.

## 9.2 Meter Commissioning and Configuration

### 9.2.1 General

Prior to meter commissioning a full documentation package should be prepared that contains the system schematic, meter functional specification, meter installation and operation manual, FAT test results, EFAT test results and any third party flow test results. If SITs have been conducted the resultant data book should also be provided. During testing some meters use a specific test configuration file that has to be changed back to the project specific file. Test and project specific configuration files should be clearly identified and the correct revisions should be indicated in both software and documentation.

Before commissioning commences, the revision levels of all software associated with the meter and facility control system should be checked against the project documentation.

On first power up, the power loads should be measured and confirmed against specification. In addition, a communication check should be completed. The meter serial numbers should be confirmed to ensure the system is communicating with the correct meter. Communication parameters, settings, and IP address should be confirmed as well as appropriate data allocation tables.

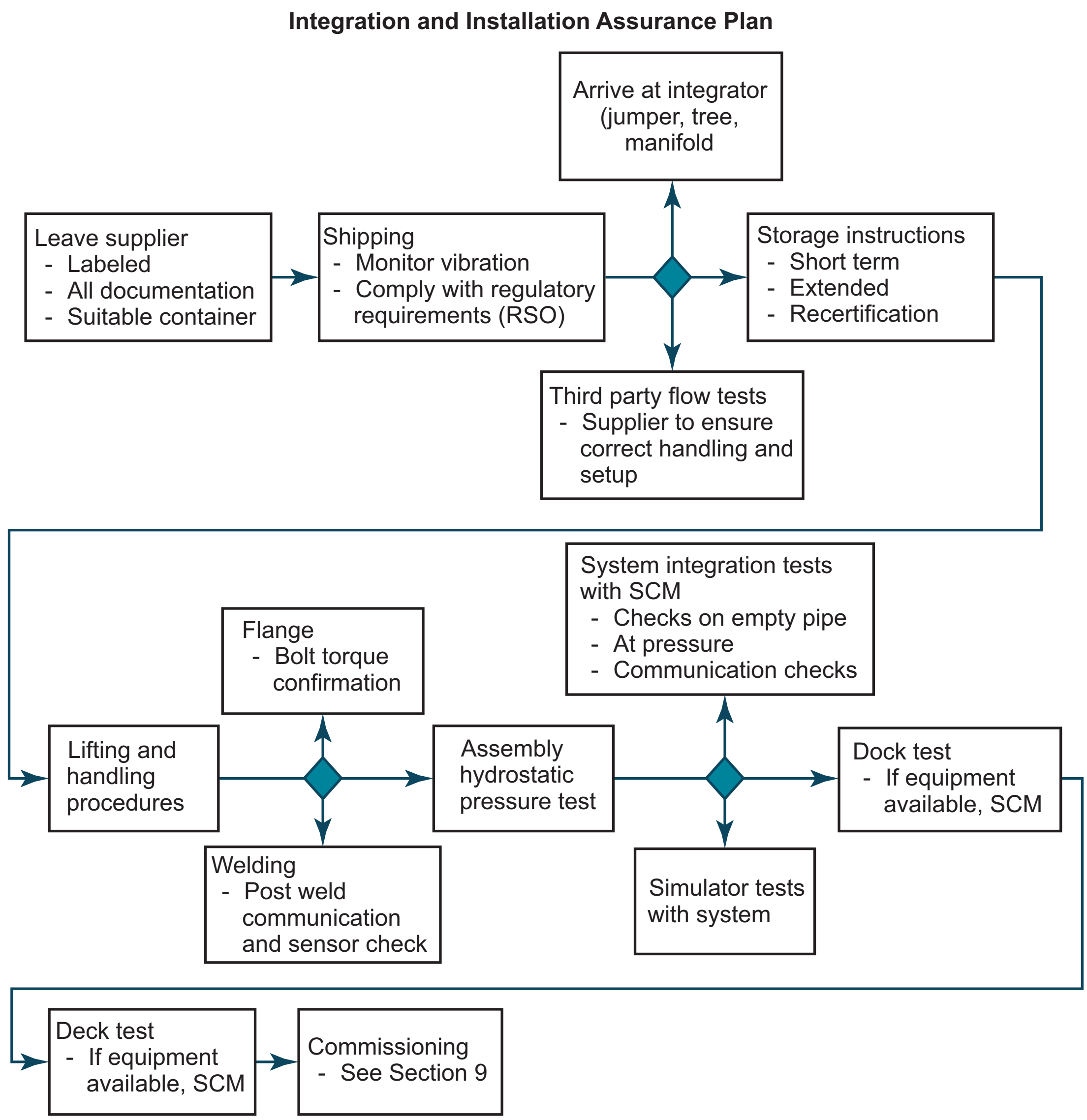


**Figure 2—Typical Flow Chart for Integration and Installation Assurance Plan**

Redundant channels should be verified by validating the automatic switch over and ensuring the voltage requirements are met.

At this point any specific supplier commissioning tests should be conducted. Meters are typically delivered ready for use and if a comprehensive Integration and Installation Assurance Plan has been followed minimal tests should be required. A self-diagnosis routine should be completed to ensure all systems are in order.

Once the meter settings have been validated, a series of static and dynamic response tests should be conducted. These tests are reliant on field operations and should be coordinated accordingly and may not occur until after preliminary commissioning.

A series of opportunistic static tests may be conducted on a number of different fluids during field commissioning, depending on the meter location. Hydrostatic pressure tests of the component the meter is integrated into may be conducted with test fluid (treated water) or methanol. The meter should be characterized for these fluids prior to installation which requires preplanning with operational activities.

In addition to static testing of meter locations, tree commissioning and flow line flushing activities offer opportunities to confirm the dynamic responses of MPFMs. The meter should respond to valve openings and depending on meter type changes in composition due to chemical injection or commissioning fluids. Dynamic responses of this nature should only be used to confirm the meter is operating and taking measurements.

During both static and dynamic tests it may be possible to check meter sensors against adjacent or local sensors on the integrated structure. Similar responses and trends should be replicated on both sets of sensors. This may be combined with a virtual metering system if available to highlight any inconsistencies or to prove matching trends and readings. These data may be valuable throughout the meter life and should be stored as required.

Note that in some circumstances the well is unloaded through the meter and is subject to completion fluids. A dedicated clean-up configuration file may be required by certain metering technologies for this scenario. Unloading a well through the meter may not be a preferred operating condition and damage could be caused by drilling fluids. Each unloading scenario should be confirmed with the equipment supplier.

#### 9.2.2 Initial Flow Tests and Fluid Samples

Fluid sampling is detailed in API *MPMS* Ch. 20.3 and is typically conducted as part of a full meter operation strategy aimed at ensuring performance and availability. Sampling may not be possible for all subsea systems and often sampling can be an opportunistic activity. The sensitivity to fluid property variations is different between the MPFM technologies available, and some MPFMs implement methods to determine changes in fluid properties through measurements and analysis of sensor data. However taking fluid samples through the meter life is generally a robust way of checking that meter configuration parameters are still correct.

The phases of commissioning detailed in 9.2 are typically conducted before hydrocarbons are flowing. There may be an extended period between meter commissioning and multiphase flow measurement and typically a change in personnel conducting the activities. There should be a handover of metering functional and operational specifications to the facility person responsible for flow measurement. This handover may include initial trials of flow measurement for the first hydrocarbons.

Initial flow measurements should cover flow tracking and verification with either a virtual meter or mass correlation system where possible. Local sensors and overall system correlation should be used to ensure the meter is producing realistic measurements. Flow rate variations are produced during control choke operation and tracking data can be quickly captured during this period.

MPFM early production sample results should be compared to the meter configuration data developed during meter specification, if possible. Maintaining correct configuration files for phase behavior and fluid properties throughout the meter field life maintains meter performance.

The collection of production samples is dependent on the field layout and operational philosophy. The goal of sampling is to gather fluid properties and pressure-volume-temperature (PVT) data to compare to initial meter configuration parameters set up during MPFM FAT. The following items may be incorporated in a sampling plan:

— duration of sample time;

— when to take a sample;

— size of sample;

— variation in samples—taking multiples;

— phase transition at STP versus flowing pressure and temperature;

— time to process a sample—onsite versus lab;

— coordination between the various disciplines that conduct sampling (e.g. reservoir management, flow assurance, production chemistry, measurement) can provide fluid information that may be necessary for the MPFM.

Sampling can be achieved through test separators, subsea equipment and workover type vessels. All interventions should be controlled as part of the overall field operation plan.

# 10 Operations and Maintenance

## 10.1 In Situ Checks

### 10.1.1 General

Meter checks during operational life should confirm the required accuracy of the meter against the potential changes in the original input parameters and meter configuration. Meter checks are distinct from controlled flow tests which are generally not possible when the meter is in operation. Long term operation of the meter should be managed by the field Operations Plan, which is outside the scope of this recommendation. However the plan should include a section on meter checks with the aim of maximizing flow meter performance. Where possible the responsible engineer should establish requirements for meter checks and work with operations to integrate them as part of scheduled activities. This should include parameters or times for when meter verification should be conducted to ensure meter accuracy is maintained. This may be based on compositional parameters, specific points in field life, or some operational boundaries. Some meter checks are executed at moments of opportunity during shutdown, start-up or other operational activities.

Generally meter checks and verifications can be accomplished by some of the following which may occur opportunistically or should be preplanned for high performance meters.

— Mass balancing for determining overall accuracy of metering by balancing the topside separation versus that measured by the meter(s). This can be achieved by looking at the meters individually, in groups or most likely a combination of both.

— Trending of virtual metering system versus MPFM results, assuming they operate independently and the MPFM has not been used to calibrate the VMS.

— Periodic checking of the meter with a test separator if possible and if the application requires it.

— Independent periodic checking of some flow assurance parameter (like water break through) at the separator to ensure it is still tracking changes.

— Sampling of production fluid for verifying meter configuration and updating, as required.

— Checking meter configuration parameters against a known fluid in the bore, e.g. during chemical/dead-oil displacement at start-up or shutdown.

For applications where meter accuracy is critical the verification methodology selected should be shown to have a suitable measurement uncertainty. Unless a dedicated proving system is used this may not be possible. Continuous or periodic tracking to a reference measurement can be used to track any potential long term changes in meter accuracy. If this is associated with changes in fluid parameters the meter may have to be reconfigured.

### 10.1.2 Field Tracking of Meter Performance

Ongoing field tracking of meter performance should be conducted as part of general operations, which are outside the scope of this RP. The responsible engineer should ensure that the meter self-diagnosis is run per supplier specification. Self-diagnosis tools should provide information on power usage, communication integrity, and sensor consistency. Typically these tools only give information regarding the mechanical status of the equipment rather than its measurement accuracy. Supplier support or review may be required for evaluating self-diagnosis reports. A datasheet summarizing meter metrics that define standard operating ranges should be produced by the supplier to assist in continued tracking.

In addition, comparison of meter sensors versus local or adjacent sensors can be used as an external reference. Historical data showing similar trends can be used as reassurance for meter integrity while divergent data may be used as confirmation for meter verification.

The PVT model used in the meters configuration file should be maintained throughout the project life based on the operation plans sampling scheme or in situ verification. Verification of the configuration file revision level and security setting should be reviewed periodically.

Maintenance of meter performance is also covered in API *MPMS* Ch. 20.3.

## 10.2 Configuration Parameters Audit Trail

Changes to the meter settings and configuration files should be managed by a suitable security program that enables only appropriate, responsible users to have access to configuration menus. A historical log of access dates and users should be maintained for all changes to the initial setup parameters. Depending on meter application these data may form part of a legal contract and should meet all requirements of that contract. Prior to making changes to the configuration file it is useful to demonstrate offline the impact that any such change has on the measurement (possibly using raw data from the meter).

Read and write access menus and interfaces should be designed for the specific users' needs.

Further information on data configuration is given in API *MPMS* Ch. 20.3.

## 10.3 Maintenance

The meter should be designed not to require any routine maintenance when operating under agreed service conditions. As per Section 7, the meter is to be designed to maximize availability and eliminate or minimize the need for maintenance. Any maintenance that is required should be done through the topside communication system where possible. Retrieval of any subsea components is not considered maintenance and is covered in 7.3.

Any physical maintenance required should be designed to be completed with the minimum of system down time. System uptime can be increased by developing maintenance plans that do not require the removal of the entire meter, that can be completed in a single intervention, that use commonly available vessels and ROVs and by having appropriate spares available locally. Where maintenance needs are identified throughout the meter life the supplier should endeavor to detail the extent, duration, methodology, and cost of executing the work scope.

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