

Erosion Management in the Oil and Gas Industry

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Foreword

Solid particle erosion and erosion corrosion has been a recognized threat to the Oil and Gas production Industry for many years. On recognition of this, substantial amount of research and technology has been developed to assess, monitor, predict and mitigate these degradation mechanisms. Testing, Inspection, monitoring and prediction modelling technologies are now available to Projects and Operations and they have overcome many of the limitations of the original guidelines on erosion and erosion corrosion addressed by Industry standards as API⁽¹⁾ 14E¹ and EEMUA⁽²⁾ 194.² This document is conceived as an opportunity to gather the current Industry wisdom as an attempt to summarize some of the procedures and criteria already put in place by many contractors and operators using the above-mentioned technology areas.

This SP provides guidance on internal erosion and erosion-corrosion management. Guidance is given for erosion and erosion-corrosion threat assessment/prediction, barrier selection, monitoring, inspection, risk assessment and data management. This SP covers mainly sand caused erosion. However, the guidance in this document can be used for other solid particles.

This SP is applicable to tubular products, e.g., tubing, pipelines, flowlines, risers, valves, and piping systems.

Equipment with complex geometries like downhole valves, intelligent completion design, and sand screens are outside the scope of this document.

Drill cuttings injection and high concentration slurries transport are outside of the scope of this SP. In this document, a high concentration slurry is considered a liquid that contains greater than 2% by volume particles.

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In NACE standards, the terms **shall**, **must**, **should**, and **may** are used in accordance with the definitions of these terms in the NACE Publications Style Manual. The terms **shall** and **must** are used to state a requirement, and are considered mandatory. The term **should** is used to state something good and is recommended, but is not considered mandatory. The term **may** is used to state something considered optional.

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Section 1: General

1.1 Erosion is defined by NACE International as “The progressive loss of material from a solid surface resulting from mechanical interaction between that surface and a fluid, a multicomponent fluid, or solid particles carried with the fluid.”

1.1.1 Erosion has two main consequences for the Oil and Gas Industry:

1.1.1.1 Operating conditions can lead to erosion and damage to equipment and potentially loss of primary containment. These consequences can have an impact on safety, environment, and operations.

1.1.1.2 Production rate can be limited to avoid erosion. If these limits are set too low, the consequence is significant and unnecessary production loss or deferment.

1.1.2 Erosion problems are frequently caused by solids. These solids may come from the following sources:

- Unconsolidated reservoirs. The rate of sand produced from reservoir is influenced by the following factors:
 - Reservoir management
 - High drawdown from subsurface artificial lift systems: ESPs, PCPs, sucker rod pump (SRPs)
 - High drawdown due to well high flow rate in naturally produced wells.
 - High Flow rates
 - Sand/Proppant used in fracking operations
- Corrosion products such as FeCO_3 , FeS , $\text{Fe}(\text{OH})_2$. See section 4.1.3.8.
- Inorganic solids from scaling water with tendency of producing carbonate scales and/or others

1.1.3 Erosion problems are likely to continue in the future because of the following reasons:

- The requirement to maintain and increase production.
- The occurrence of multiphase flow (i.e. slugging in the transport of production fluids in both existing and new projects).
- Continued development of sand-production-prone reservoirs.

1.1.4 Many flow dependent wastage mechanisms are termed “erosion.” For produced fluids, there are three main mechanisms to be considered:

- Erosion by fluids through liquid droplet impact. This requires very high fluid velocities in gas-dominated multiphase flow.
- Erosion by non-corrosive fluid carrying solid particles. Also applicable to low corrosivity fluids overwhelmed by the mechanical action of the metal removed by the solid particle impingement.
- Erosion-corrosion by a corrosive medium containing solid particles. For conditions where both erosion and corrosion are recognized as important contributors to the total metal wastage. Erosion-corrosion can also happen at high velocity in presence of droplets.

1.1.5 High flow rates may enhance corrosion by increasing mass transport of corrosion products and reactants, but this is not to be confused with erosion-corrosion as no mechanical removal of material is involved.

1.1.6 There are cases when small content of solids, even below typical detection limits, may trigger erosion-corrosion as per mechanism described in the third bullet point in 1.1.4.

1.1.7 These definitions can easily be distinguished on paper by degradation mechanisms, but in real practice these mechanisms are often not absolute, and they may be distinguishable and defined by the significance of the contribution of either corrosion or erosion and the consequent mitigation method used to minimize the wastage. For example, an erosion-corrosion problem on carbon steel subject to nominally solid free corrosive production (per EEMUA 194 definition) might be effectively resolved using a corrosion resistant alloy (CRA), hence for practical purposes the damage mechanism is often classified as Corrosion.

1.1.8 Erosion and corrosion can be independent of each other, in which case the total wastage is the sum of the wastage produced by each mechanism in isolation, or synergistic, in which case the total wastage is greater than the sum of the independent processes of erosion and corrosion taken separately.

1.1.9 Erosion caused by cavitation occurs as result of the formation and collapse of bubbles at or near the surface which result in material removal. Cavitation is a threat in high velocity fluid flow with sudden changes in pressure.

Section 2: Terms and Definitions

For the purpose of this SP, the following terms and definitions apply:

Barrier: A design, construction or operational activity that manages threats due to erosion, preventing the threat from developing into an event.

Barrier monitoring: A measurement of the performance of a barrier.

Erosion: The progressive loss of material from a solid surface resulting from mechanical interaction between that surface and a fluid, a multicomponent fluid, or solid particles carried with the fluid.

Erosion-Corrosion: A conjoint action involving erosion and corrosion in the presence of a moving corrosive fluid or a material moving through the fluid, leading to accelerated loss of material.

Erosion rate: The time-rate of metal loss due to erosion. It is typically expressed in as penetration per unit time, e.g., (mm/year or mpy).

Likelihood: In common use, this is an estimate of the expected probability or frequency of occurrence of an event. Typically, descriptors are used rather than a number e.g. 'very likely' or 'likely to occur several times during the life of the equipment.'

Threat: A damage mechanism that results in the degradation of a component, circuit or system.

Threat (Credible): A credible threat is one that is expected to produce degradation in a system, circuit or component. Credible threats depend on the barriers that are in place.

Section 3: Erosion Management—Overview

Erosion is a potential safety risk to operations and can cause production deferrals and high repair costs.

Erosion management shall comprise these steps:

- Erosion threat assessment
- Identification, implementation and management of barriers for each erosion threat
- Monitoring of barrier effectiveness.
- Monitoring of erosion rates.
- Inspection program.
- Performance management.

The sections that follow describe the erosion management process.

Section 4: Erosion Threat Assessment

The first step in managing erosion in projects and operations shall be to assess the erosion threat. The flow chart in Figure 1 describes the process for evaluating the erosion threat and the procedure to quantify it. Instructions for use of the flow chart are described in the next sections. The titles of the sections correspond to the labels for each box in Figure 1.

4.1 Data collection

- 4.1.1** The first step for erosion threat assessment is to collect the necessary input data. The threat assessment will only be as good as the input data used, such that care needs to be taken to ensure their validity and accuracy. The data listed in Table 1 should be gathered to perform an effective erosion threat assessment. When it is not possible to obtain field specific data, the values should be estimated from other sources. Both subsurface and facility disciplines should be consulted to ensure that the most appropriate data relative to sand production and operating conditions are used.
- 4.1.2** The parts in bold in the table indicate those parameters that shall be used as minimum required inputs for erosion models.
- 4.1.3** Solid particles data

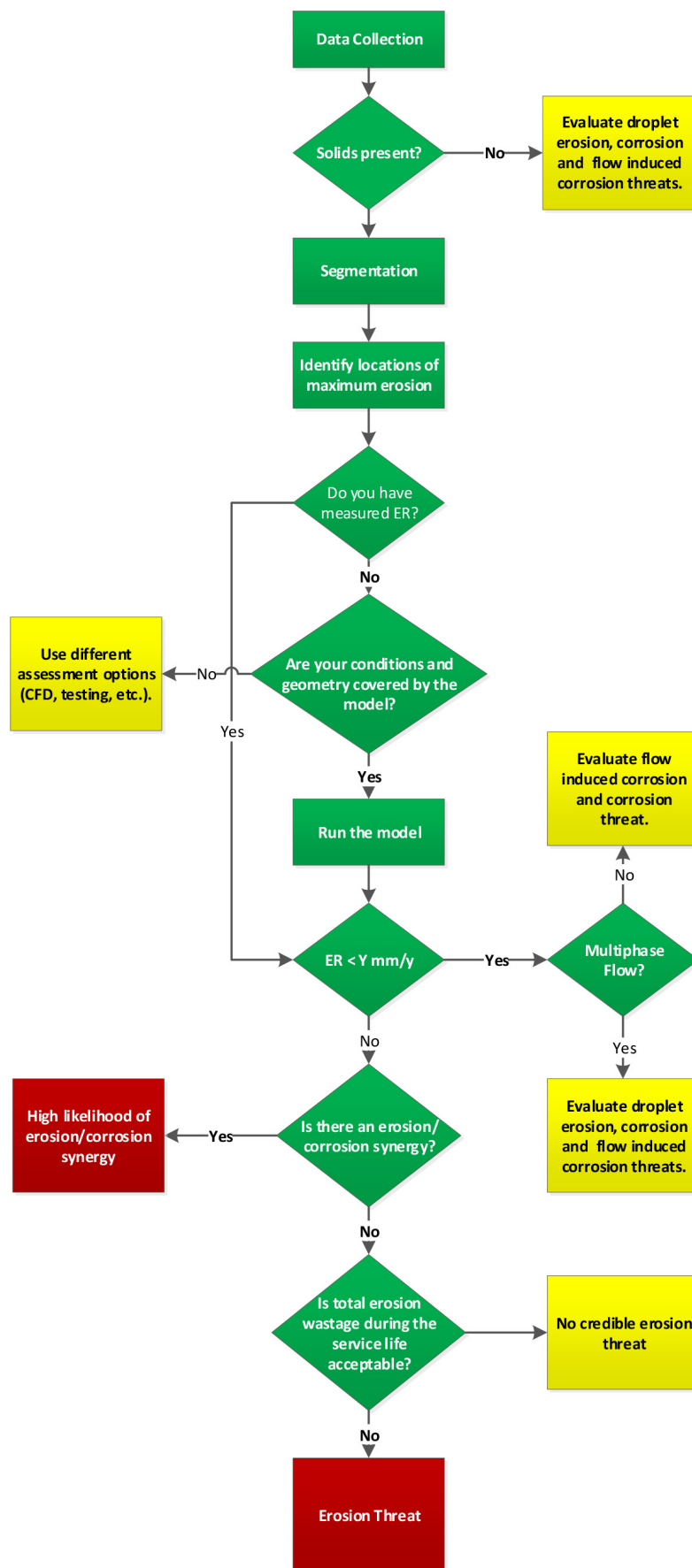


Figure 1: Erosion threat assessment guideline flow chart. In the figure the following abbreviations are used:
ER = Erosion Rate, CFD = Computerized Flow Dynamics.

Table 1
Erosion Threat Assessment Input Data

Solid Particles Data	Geometry and Material Data	Gas Data*	Liquid Data*
Production rate (e.g., lbs/day, pptb,** lbs/mmscf)	Type of geometry (e.g. Elbow, Tee, ...)	Superficial gas velocity (Vsg) or Gas flow rate	Superficial water velocity (Vsw) or water flow rate
Solid particles size or particle size distribution	Pipe internal diameter (for fittings provide elbow radius and changes in ID as applicable)	Gas viscosity	Superficial oil velocity (Vso) or oil flow rate
Shape	Material type/grade	Gas density	Water density and viscosity
		Gas Composition	
Density	Material hardness		Oil density and viscosity
Chemical Composition			
Hardness		Flow regime	
*In-situ properties required, otherwise temperature and pressure and fluids composition are needed.			
**pptb = pound for thousand barrels			

4.1.3.1 The following particle-related input data shall be used to perform the erosion threat assessment:

- Loading (sand loading—sand production rate).
- Size distribution.
- Shape.
- Density and hardness.

4.1.3.2 There are different solid particles in oil and gas production including sand, corrosion and scaling products, proppant, hydrates, etc. Sand is a common solid particle found in oil and gas production streams and the main cause of erosion in the Oil and Gas Industry. However, proppant, corrosion products, scales and other solid particles can be erosive too, depending upon the fluid and flow characteristics.

4.1.3.3 Solid particle data gathering during design stage

4.1.3.3.1 Estimation of solid particle data during the design stage should be done using information collected from operating analogue wells (e.g., the same reservoir, the same region, or exploratory wells). The following are some guidance regarding erosion threat assessment in projects:

- Presence of Sand screen and/or gravel pack: The maximum sand size that can pass through the gravel pack and sand screen, should be used for erosion threat assessment.
- Absence of sand control sand screen: Sand distribution should be used to evaluate the erosion threat. In some situations, flow back of proppant may also be evaluated.
- The project needs to prescribe the mitigation measures that should be taken when a sand control completion fails (partially or fully). This procedure will prescribe flow rate reduction until sand production is reduced to acceptable levels (or requires the well to be shut-in). It should also define the acceptable sand loading levels for continuous operation in alignment with the expected flow rates. Operating decisions in the event of downhole completion failure should be fit-for-purpose and tubular dimensions for both wells and surface facilities updated over time depending upon the level of threat.

4.1.3.4 Solid particle data gathering during operations

4.1.3.4.1 In operations, several techniques for collecting solid particle data may be used. The preferred technique is sampling. Sampling can be performed at the sampling points, in separators and other vessels if sand is accumulated there, in filters, and in pig returns. See section 7.1 for more details on solid sampling.

4.1.3.4.2 Sand and erosion monitoring may be also used to obtain data on sand loading or sand production rate. See Section 6 for more details on sand and erosion monitoring.

4.1.3.5 Solid particle loading

4.1.3.5.1 Erosion rate increases linearly with the increase in solid particle loading for relatively low sand concentrations (typically below 2% volume for slurries and 0.01% by volume for gas dominated flows). The best sources of data on sand loading are obtained from actual operating conditions or from analogues (understanding of the reservoir characterization, how the well has been completed (sand screens, Artificial Lift Systems [ALSS]), experience). If there is a high uncertainty on solid particle loading, the minimum amount that can be detected should be used in equipment design. In this case, alarms should be set at this sand loading value and procedures will be put in place on actions to be taken when the alarm becomes active. Refer to section 6.14 on acoustic sand detectors to obtain these values. EEMUA 194 have defined the nominally “solids free” production as less than 1 pptb for liquid flow, or less than 0.1 lb of solids per mmscf of gas. These values may be used as the minimum sand loading for erosion estimations when no information is available on sand production rate.

4.1.3.5.2 Representative solid production rates and their relative duration should be used. In most cases, sand production is not constant in time, but it comes in bursts of high sand production. It might be necessary to run different scenarios with different sand production rates to evaluate the erosion threat.

4.1.3.6 Solid particle size distribution

4.1.3.6.1 Erosion rate generally increases with the increase in particle size. The use of particle size distribution instead of a single size may provide a more representative estimate of the erosion rate. Representative samples of solid particles should be obtained whenever possible. See section 7.1 for more details on sampling.

4.1.3.6.2 The best results are obtained using the actual sand size for erosion threat assessment. A first assessment may be performed making an evaluation of the most probable sand size. However, erosion calculations shall be repeated as soon as produced sand size data are obtained from the field and if the particle size is different from the one used in previous calculations.

4.1.3.6.3 In real practice it is difficult to separate the effect of particle size from particle shape.

4.1.3.7 Particle shape

4.1.3.7.1 Erosion rates caused by sharp solid particles are higher than for round particles at the same flow conditions. Figure 2 shows an example of particle shapes and relative shape factors. The user should use this figure to assign the shape factor. If the particle shape is not known, the user shall assume sharp particle shape in the erosion assessment. The shape factor is used by some models as a multiplying factor. It is expected that erosion rates would be higher with larger shape factors. Shape factors equal to 1, will not have any dampening effect on the estimated/calculated erosion rates.

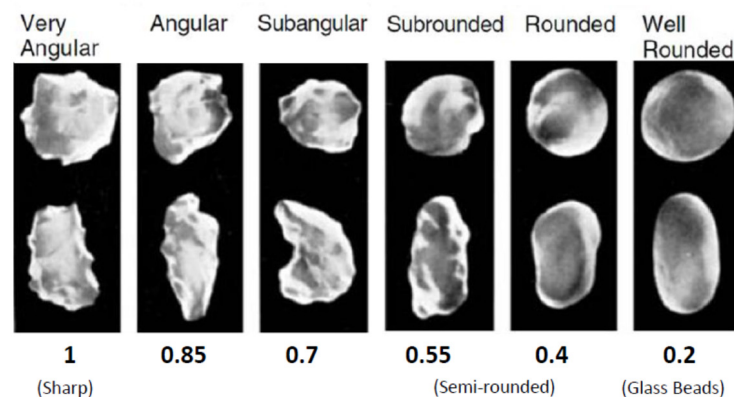


Figure 2: Solid particle shape and relative shape factor

Table 2
Physical Properties of Erosive Particles

Name	Formula	Density, g/cm ³	Mohs' Hardness
Diamond	C	3.5	10
Silicon Carbide	SiC	3.2	9-10
Aluminum Oxide	Al ₂ O ₃	4.0	9
Tungsten Carbide	WC	15.8	9
Zirconia	ZrO ₂	5.8	8
Quartz	SiO ₂	2.6	7
Magnetite	Fe ₂ O ₄	5.2	6
Glass Bead	SiO ₂	2.4	5.5
Chalk	CaCO ₃	2.7	3
Barium Sulfate	BaSO ₄	4.5	3

4.1.3.8 Solid particles density and hardness

4.1.3.8.1 Solid particles density and hardness are also a determining factor in erosion rates experienced in service. Particles with higher density are more erosive than lighter particles. Using solid particles density distribution will give more accurate erosion threat evaluation.

4.1.3.8.2 If the solid particle density and hardness is not known, the user should run different scenarios with different sand densities to evaluate the erosion threat. A typical sand density of 2650 kg/m³ may be used. The effect of the particle hardness has been less studied, in general harder particles should be more erosive than softer ones. A parameter of more relevance is the relative hardness of erodent material compared to the target material. Salt deposits and soft silicates with hardness below the hardness of steel can be up to 100 times less erosive³ than sand (SiO₂), which hardness is significantly higher than steel.

4.1.3.8.3 If the hardness of the particle is greater than the hardness of the target material (sand to steel hardness for example), increasing the hardness of the particle further (as in SiC) would not significantly increase the erosivity of the system on steel. However, a harder particle such as SiC can be up to 10 times more aggressive⁴ than SiO₂ for a given system when the target materials is a Tungsten Carbide component, which is harder than sand but softer than SiC.

4.1.3.8.4 Density and hardness of different solid particles are shown in Table 2.

4.1.4 Equipment geometry

4.1.4.1 Erosion severity is very dependent on flow geometry. Changes in velocities due to changes on internal diameter, changes in flow direction and flow pattern have a big impact on erosion, and they depend on the equipment geometry. For example, the following geometries are ranked according to erosion severity (high to low): direct 90° impingement, standard short radius 90 elbows, tees, 3D bends, 5D bends, flexible pipe, and weld joints.

4.1.4.2 The threat assessment should be performed on final or as-built equipment drawings. For example, for piping systems all elbows, bends, restrictions/expansions, and any geometrical discontinuity that can disturb the flow should be included in the erosion threat assessment.

4.1.5 Fluid data

4.1.5.1 The following data should be collected for the erosion threat assessment:

- Flow rates
- Single or multiphase flows
- Flow regime.
- Superficial/in-situ velocities of each phase (oil, gas, water).
- In-situ fluid properties, density and viscosity of each phase.
- Pressures and temperatures.

Table 3
Physical Properties of Common Engineering Materials

Description	Density, g/cm ³	Approximate Hardness kg/mm ²
Silicon carbide	3.2	2200
Alumina ceramic (99.5%)	3.9	1600
Cemented tungsten carbide 6% Co	14.9	1500
Cemented tungsten carbide 6% Ni	14.9	1400
Cemented tungsten carbide 9% Co	14.6	1350
Partially stabilized zirconia (Y)	6.0	1300
Carburized steel 60 HRC	7.9	700
Tool steel UNS T41907	7.8	650
Cobalt alloy R30001	8.7	620
Stainless steel UNS S17400 H900	7.8	510
Cobalt alloy R30006	8.4	430
Hardened steel 40 HRC	7.9	390
Cobalt alloy R30021	8.3	350
Low hardened steel 22 HRC	7.9	250
Stainless steel UNS S31600	8.0	240
Annealed steel 89 HRB	7.9	180
Brass UNS C46400	8.4	150
Aluminum UNS A96061 T6	2.7	120

4.1.5.2 Flow regime calculations should be completed before starting erosion threat assessment. Specialized models may be used for flow regime calculation. In lieu of in-situ fluid properties, pressure, temperature and fluids composition may be used to predict in situ conditions by appropriate models.

4.1.5.3 The flow conditions may change during the operating life of the asset. Using the flow conditions at different time intervals (e.g. early, middle and late life) increases the prediction accuracy.

4.1.6 Materials

4.1.6.1 Material characteristics like hardness and ductility influence the erosion rate. For this reason, the material type and relative hardness are needed. Some models have been developed for the more common used materials and the role of material characteristics is included in the model.

4.1.6.2 Density and hardness values for several engineering materials are shown in Table 3.

4.2 Segmentation

4.2.1 For an effective erosion threat assessment, the asset should be divided in parts (segments) that have similar conditions. Each segment has the following characteristics:

1. Similar fluid characteristics: Gas to liquid ratio (GLR), viscosity, water cut,
2. Similar flow characteristics: flow rate, superficial velocities of the different phases.
3. Similar solid particle characteristics: loading, size distribution, density, hardness, shape.

4.2.2 If a segment affects the flow pattern in its adjacent segment, then this change in flow pattern should be addressed in the erosion rate assessment. Common industry practice is that if there are less than 10 internal pipe diameters of straight pipe upstream of a fixture being modeled the influence of elbows, bends, and valves need to be addressed.

4.2.3 An example of different erosion rate assessment segments for a production system is discussed in Annex A.

4.3 Identifying locations of maximum erosion

4.3.1 For each segment the location of maximum erosion threat shall be identified. Identifying the location of maximum erosion is helpful because it helps accomplish the following:

- Identify the geometry to be used in erosion rate evaluation using erosion models.
- Identify locations where the application of erosion resistant materials/coatings or other mitigation(s) may be beneficial.
- Identify the locations where to permanently install monitoring devices (PIM) and identify monitoring objectives.
- Determine the location of acoustic sand detectors and erosion probes
- Guide the inspection program

4.3.2 The location of the maximum erosion threat can change with change in flow conditions. The assessment of the locations of maximum erosion should be repeated when there is a change in flow conditions.

4.4 Do you have measured erosion rate?

4.4.1 If there are measured erosion rates in the equipment under evaluation, these measurements should be used for the erosion assessment. Experienced erosion rates shall be used only if the future conditions (see 4.1) will be like those experienced by the equipment in the past. If future conditions are predicted to be different, then the answer to this question shall be “No,” and the erosion models shall be used.

4.5 Solids present?

4.5.1 When answering ‘No’ to this question, it means that no solid particles are present in the fluids.

4.5.2 Solid particle data gathering during design stage

4.5.2.1 Estimation of solid particle data during the design stage should be done using information collected from operating wells in the same reservoir, the same region, or exploratory wells (i.e., information from analogues).

4.5.2.2 The following is some guidance regarding the likelihood of the presence of sand aiding in the erosion threat assessment (the type of reservoir is tightly related to the sand amount depending on the production method and must not be overlooked):

- Type of reservoir:
 - Consolidated versus non-consolidated. Non-consolidated reservoir will have higher likelihood of producing sand/solid.
- Fracked reservoir—Reservoirs that are or have been fracked have also high likelihood of the presence of sand/solids. Specially during the period of flowback.
- The presence and amount of sand depends on the well production method:
 - Naturally produced—high flow rates
 - ALS:
 - Electric submersible pumps (ESP) higher likelihood
 - Progressive cavity pump (PCP) medium likelihood
 - Sucker rod pumps, low likelihood.

4.5.3 Solid particle data gathering in operations

4.5.3.1 The user should be able to prove that there is no solid particle presence in the fluids or it is in such small quantity that it is not likely to cause any erosion damage. This means that there is no sand observed in sampling, filters, separators, or any other place where sand can be trapped.

4.5.3.2 Fines shall be considered solid particles.

4.5.3.3 Even when acoustic sand monitoring gives no indication of solid particles, there can still be solid particles in the system, but the solid particle production rate is less than the minimum detectable amount. The minimum detectable solid particle loading varies with flow rate, fluid viscosity, solid particle size, geometry of equipment, and the location of the acoustic sand detector (ASD). Therefore, the amount of detectable solid particles should be carefully determined when performing an erosion threat assessment.

4.6 Are your conditions and geometry covered by the model?

- 4.6.1** The erosion models available may have some limitations and may not be able to simulate all the cases found in service. These limitations are mainly relative to input parameter ranges and available geometries. Erosion models should not be used outside of their limits. If the conditions are outside the model limits, computational fluid dynamics (CFD) simulations or testing should be used. See 4.7.2 for guidance on the use of models.

4.7 Run erosion model

- 4.7.1** The erosion model selected by the facility operator should be run. There are several erosion models that claim a similar level of functionality (see 4.7.2).

4.7.2 Use of Erosion Models

- 4.7.2.1** API RP 14E¹ Section 5.5.1 shall not be used for calculating threshold flow velocity and sizing pipes containing solid particles. A body of research related to erosion and erosion-corrosion over the last 30 years, has shown that this practice neglects the impact of flow-regime dependent erosion characteristics and solids loading. In addition, the recommended practice fails to provide an adequate empirical foundation that correlates wear characteristics to C-Factor in oil and gas systems.

- 4.7.2.2** The user of this standard is responsible to select the appropriate model applicable to their conditions of interest. The erosion model should be validated by direct comparison with actual erosion data collected from either field experience or laboratory testing. Actual input parameter may vary from model to model, but as a minimum the input variables described on Table 1 and represented in bold shall be used in the models and the erosion calculations. Madani Sani et al. gives a review of existing models.¹⁷

- 4.7.2.3** Empirical methods and mechanistic modeling approaches (including CFD methods) are allowed if the models have been validated for the specific conditions of interest. Erosional threshold velocity may be computed based on the erosion rates prediction output from the models in combination with the desired service life, and minimum acceptable remaining wall for the given application.

4.8 Erosion rate < Y mm/y

- 4.8.1** If the erosion rate is higher than Y mm/y (“No” response to the question) in corrosive environments, there is a high probability of erosion and corrosion synergy for carbon/low alloy steels and 13% Cr stainless steels. The Y value should be approved by the facility operator. Different oil and gas operators have used different Y values; some have used 0.1 mm/y (4 mpy), others 0.025 mm/y (1 mpy). In the case of erosion/corrosion synergy, the erosion-corrosion rate will be higher than the sum of erosion and corrosion rates. Conditions where there is potential for erosion/corrosion synergy should be avoided.

- 4.8.2** If the erosion rate is less than Y mm/y (“Yes” response to the question), the two phenomena, erosion and corrosion, can be calculated separately and the sum of the two effects will determine the expected life of the equipment.

- 4.8.3** The erosion rate can be considered alone in non-corrosive environments.

- 4.8.4** In all cases (even when the predicted erosion rate is less than Y mm/yr), make sure that there is adequate wastage allowance for the erosion rate predicted.

4.9 Multiphase flow?

- 4.9.1** If the answer to the question is “No,” there are no erosional velocity limits for purely single phase, solid free, non-corrosive liquids (no entrained gas) or gases (no entrained liquid). However, other flow related phenomena need to be evaluated such as cavitation,⁽³⁾ noise/vibration, friction pressure loss, and water hammer.⁽⁴⁾ In the case of corrosive fluids, flow induced corrosion and corrosion threats should be evaluated.

- 4.9.2** If the answer is ‘Yes,’ there is a potential threat that droplet erosion in gas condensate streams in the absence of any solid particles by non-corrosive fluids. A mixture velocity of 70 m/s has been used in the past.⁵ Recent studies have shown the actual velocities to achieve droplet erosion are significantly higher than 70 m/s and under special circumstances higher flow rates may not bear a threat. However, the high flow velocities will pose significant potential risk should any change in the operations lead to small amounts of solids entrainment. Therefore, erosion predictions modeling considering small amounts of solid particles, and mitigation

⁽³⁾Where liquid pressure is at or near the bubble point pressure, bubbles can form at regions of localised pressure drop. These bubbles can then implode abruptly at points where the local pressure rises again above the bubble point pressure. These implosions can cause removal of material (cavitation) and/or noise problems.

⁽⁴⁾Water hammer results from the shock pressure due to the sudden stopping of a liquid (e.g. when closing a valve or where reciprocating pumps or compressors are used). The magnitude of this pressure shock is a function of the fluid velocity, the stoppage time and the elasticity of the pipe. The accompanying mechanical vibrations can result in fatigue failure if corrective actions are not taken.

measures such as implementation of inspection and sand/erosion monitoring should be added when exploring possibilities to safely increase the production rates above this limit. The impact of erosion-corrosion and corrosion should be investigated.

4.10 Is there an erosion/corrosion synergy?

4.10.1 For erosion rates higher than Y mm/y there is a possibility of erosion/corrosion synergy. This is more pronounced in carbon and low alloy steels up to 13% Cr stainless steel. The threat of erosion/corrosion synergy for Super 13% Cr and higher alloyed steels is low and may happen in very corrosive conditions.

4.10.2 If the response is “Yes,” the user shall evaluate erosion-corrosion synergy threat as this form of damage is highly likely.

4.11 Is total erosion wastage over the service life acceptable?

4.11.1 The acceptable erosion rate depends on the erosion allowance, or the amount of wall thickness that can be consumed for the equipment to remain fit for service.

4.11.2 Erosion allowance = Actual Thickness - Minimum Acceptable Wall Thickness

4.11.3 When cladding with corrosion-resistant alloy (CRA) is used, a minimum clad thickness of 1 mm is needed at the end of the design life to provide corrosion resistance.

4.12 No erosion threat

4.12.1 This means that the erosion threat is low for the evaluated conditions.

4.12.2 However, the user shall evaluate if the erosion allowance is sufficient for the remaining life of the equipment even for erosion rates below Y mm/y.

4.13 Erosion threat

4.13.1 When there is erosion threat, the operator shall implement mitigation barriers and/or a surveillance program (See Section 5, 6, and 7).

4.14 Erosion-corrosion threat

4.14.1 Erosion-corrosion occurs in environments which have the potential to be both erosive and corrosive. Erosion and corrosion can be independent of each other, in which case the total wastage is the sum of the wastage produced by each mechanism in isolation, or synergistic, in which case the total wastage is greater than the sum of the independent processes of erosion and corrosion. Erosion and corrosion rate cannot be simply added to calculate the total erosion/corrosion rate because of the synergy effect.

4.14.2 A maximum allowable erosion rate for materials that are prone to synergistic erosion/corrosion (i.e. carbon/low alloy steels and 13% Cr stainless steel) has been estimated to be 0.1 mm/y by some operators. It is the responsibility of the operator to validate the erosion rate that would trigger erosion/corrosion synergy. If the erosion rate is maintained below this limit, the threat of synergistic erosion-corrosion is considered to be acceptably low.

4.14.3 In the case of Super 13% Cr stainless steel and higher CRAs (e.g. duplex stainless steels, highly alloyed austenitic stainless steels, nickel alloys) no maximum allowable erosion rate has been set, because there is no threat of erosion and corrosion synergy when exposed to production fluids (certain operations may trigger erosion/corrosion synergy, e.g., acidizing jobs). In these cases, the maximum allowable erosion rate shall be determined by the wastage allowance available.

4.14.4 Assessment of the synergistic erosion corrosion mechanism has been more controversial topic in the industry for years. Common wisdom is that the most susceptible alloy in the oil and gas industry is carbon steel under film forming conditions. At high erosivity conditions, carbon steel may experience erosion-corrosion rates much higher than bare metal corrosion rates. In such conditions, erosion-corrosion rates are dominated by the corrosion component of the damage mechanism. Even at low erosivity conditions, removal of pseudo-protective iron carbonate layers on carbon steel by the mechanical action of solid particle impingements can increase metal wastage rates to rates higher than bare metal corrosion rates.

4.14.5 At similar conditions, the 13Cr is still able to either maintain its passivating film or to re-passivate fast enough (re-healing of the Cr-Fe oxide layer) to hold the total metal wastage rate to within acceptable limits. This remains true for multiphase flows involving CO₂ and sand if the corrosivity of the sand-bearing fluid is relatively low

- 4.14.6** When erosivity and corrosivity conditions are severe enough, the removal of passive films in some CRA's could overcome the ability of the passive film to reform enabling large erosion-corrosion rates.
- 4.14.7** Other higher alloyed CRA's, such as super martensitic stainless steel, have shown reduced synergistic effects of erosion-corrosion as compared to the 13 Cr-L80^{6,7} and at similar conditions, higher grade alloys such as duplex stainless steels can completely curb the synergistic effect at severe erosivity conditions for pure erosion rates found in production environments.
- 4.14.8** Some rules of thumb have been developed in the past to set a maximum allowable erosion rate for materials that are prone to synergistic erosion-corrosion (i.e. 0.1 mm/yr for carbon/low alloy steels and 13% Cr stainless steel). Industry has also developed some erosion corrosion models, but those have been much less validated than the pure erosion or pure corrosion models now available and therefore they should be used with caution and seeking for validation on a case by case basis.

4.15 Computational Fluid Dynamics

- 4.15.1** Computational Fluid Dynamics (CFD) may be used to identify the location of the erosion scar (the location of maximum erosion damage). CFD may also be used to estimate erosion rates for equipment with complicated geometries that are not covered by the erosion model.

4.16 Laboratory erosion assessment

- 4.16.1** Laboratory erosion assessment may be used to determine erosion rates when the erosion models or CFD are not reliable for the conditions under evaluation, or to validate erosion model and/or CFD results.
- 4.16.2** There is currently no NACE standard practice regarding erosion testing.
- 4.16.3** To perform a service erosion assessment in the laboratory the user should simulate field conditions (e.g., particle characteristics and size distribution, substrate properties, particle impinging angles and velocities, fluid characteristics) and equipment geometry, which cannot typically be fully represented in a single laboratory test. Testing in flow loops has been frequently used to evaluate erosion threat. However, no standards are available for this type of testing.
- 4.16.4** Erosion subject matter experts (SME) should be consulted to assess the need for testing and to build a testing program that simulates field conditions and to properly analyze the results. The following is a list of erosion testing related standards:
- ASTM G32: Standard Test Method for Cavitation Erosion Using Vibratory Apparatus⁸
 - ASTM G73: Standard Test Method for Liquid Impingement Erosion Using Rotating Apparatus⁹
 - ASTM G211: Standard Test Method for Conducting Elevated Temperature Erosion Tests by Solid Particle Impingement Using Gas Jets¹⁰
 - ASTM G134: Standard Test Method for Erosion of Solid Materials by Cavitating Liquid Jet¹¹
 - ASTM G190: Standard Guide for Developing and Selecting Wear Tests¹²
 - ASTM G119: Standard Guide for Determining Synergism Between Wear and Corrosion¹³

4.17 Corrosion inhibition and synergistic erosion-corrosion

- 4.17.1** The synergy between erosion and corrosion may be mitigated by the introduction of a corrosion inhibitor. These chemicals mitigate the corrosion rate and may also reduce the rate of erosion-corrosion to the baseline erosion rate.
- 4.17.2** Solid particles can affect the corrosion inhibitor performance by mechanical removal of the inhibitor from the metal surface, by adsorbing corrosion inhibitor and reducing the effective inhibitor concentration in the solution. Therefore, the corrosion inhibitor should be qualified for the presence of solids expected in service.

Section 5: Barriers

The purpose of this section is to review erosion threat barriers that may be used in projects and operations. The selection of erosion barriers is based on the erosion threat assessment.

5.1 Barriers for erosion threat in projects

5.1.1 The following barriers may be used for erosion threat reduction:

- Sand exclusion.
- Sand removal.
- Equipment design (e.g., pipe sizing, layout, routing, piping bends, choke valves, isolation valves and water injection pumps).
- Selection of erosion resistant materials.
- Internal lining with erosion resistant materials (e.g., carbides, ceramics, diamond).
- Selection of erosion resistant coatings.
- Definition of operating limits.

5.1.2 Sand exclusion and sand removal

5.1.2.1 There are four main categories of sand control:

1. Reservoir management
2. Sand exclusion completions, where downhole sand control is designed to keep all but the smallest grains of sand in the formation using sand screens and gravel packs.
3. Sand management completions, where formation sand is predicted and can be produced.
4. The use of sand separators either downhole or downstream of the well head.
5. Well production management, e.g. well bean up, drawdown management, production optimization.

5.1.2.2 The results of the sanding study should be used to help decide whether a sand control completion is needed. Analogous well data is normally available to assist planning for unexpected events such as completion failure or other conditions where actual sand production is greater than anticipated.

5.1.3 Equipment design to minimize erosion

5.1.3.1 Piping sizing, layout, and routing

5.1.3.1.1 Several techniques may be used in the design of equipment to reduce or even avoid erosion.

5.1.3.1.2 For a given flow rate, larger pipe diameters should be used to reduce flow velocity, and consequently reduce erosion rate. However, reduction of flow velocities can also cause the sand to settle down inducing other problems, e.g., under deposit corrosion. Another method is “twinning,” in which the flow is split into two lines, with the resulting reduction in flowing velocity in each of the individual lines.

5.1.3.1.3 When practical, a separation between any change of direction of the flow and a distance should be at least 10 ID to allow for the uniform flow to re-establish.

5.1.3.1.4 Erosion damage is generally associated with changes in direction; therefore, in the design phase the number of changes in flow direction (e.g., elbows, bends, tees) should be minimized, and the pipe routing should be as direct as possible.

5.1.3.1.5 With respect to flow regime, slug flow and mist annular flow can produce high erosion rates and thus they should be avoided. Slug flow carries the sand in the crest of the wave and impinges directly onto the pipeline inner wall surface. Mist flows, can carry small sand particles and fines within droplets, causing them to impinge against the inner wall of pipeline surface. If possible, during the life of the asset, these conditions should be avoided. During the design stage, designing the installations (e.g., pipe size, layout, routing) as hydrodynamically friendly as possible reduces erosion, erosion-corrosion and flow effects on corrosion.

5.1.3.1.6 Pipe elbows are usually forged and have a bend radius of either 1 diameter (short radius) or 1.5 diameters (long radius). Pipe elbows should be minimized in solid particle containing service.

Table 4
Example of the Order of Preference for the Changes in Flow
Direction in Gas and Liquid Piping Systems

Gas Service	Liquid Service
10D	10D
5D	5D
3D	3D
1.5D	1.5D
Target tee	Target tee—not recommended
Note: Most of the production flows are multiphase and decision on the geometry of changes in flow direction will be based on the analysis of the flow parameters and erosion threat through life of the field.	

5.1.3.1.7 If elbows are used due to space limitations or other reasons, the guidance below should be followed:

1. Use long radius (1.5D or higher) elbows.
2. Use increased elbow wall thickness compared to adjacent piping for additional erosion/corrosion allowance.
3. Make sure that internal diameter at the joints between pipe elbows and other pipe fittings are aligned (no offset).

5.1.3.1.8 Pipe bends (also called pulled or sweeping bends) should be used instead of pipe elbows. The following applies to bends:

1. Are formed from straight sections of pipe.
2. Have larger bend radii than pipe elbows (typically 3 D or 5 D).

5.1.3.1.9 Plugged tees may also be used for 90° change in direction of pipe work in presence of solid particles.

1. These pipe fittings are essentially a tee that has one of the main branch outlets blocked off with either a cap or a blind flange.
2. These pipe fittings can also be referred to as “blinded tees,” “cushion tees,” “flanged tee,” “capped tee,” or “target tees.”

5.1.3.1.10 Both modeling and flow loop tests performed at University of Tulsa have shown that, for flow streams with predominantly liquid flow, plugged tees are of no benefit and can even be detrimental. For this reason, plugged tees should not be used for predominantly liquid service.¹⁴

5.1.3.1.11 In some cases, the stream can start as a gas only and the amount of liquid can increase with time. In these cases, evaluate carefully the effect of liquid content on erosion rate of plugged tees.

5.1.3.2 Restrictions in the Pipe Bore (Including Valves, Flowmeters and Reducers)

5.1.3.2.1 Restrictions in the pipe bore accelerate the flow and can concentrate particles downstream forming a jet that can hit elbows or bends, as illustrated in Figure 3. This type of configuration has been shown to accelerate erosion significantly and has caused pipe-work failures in the field; therefore, it should be avoided.

5.1.3.2.2 This type of restriction can be caused by a reduced-bore valve, a reduction in pipe bore, and some flow meters (e.g., venturis, orifice plates and vortex meters).

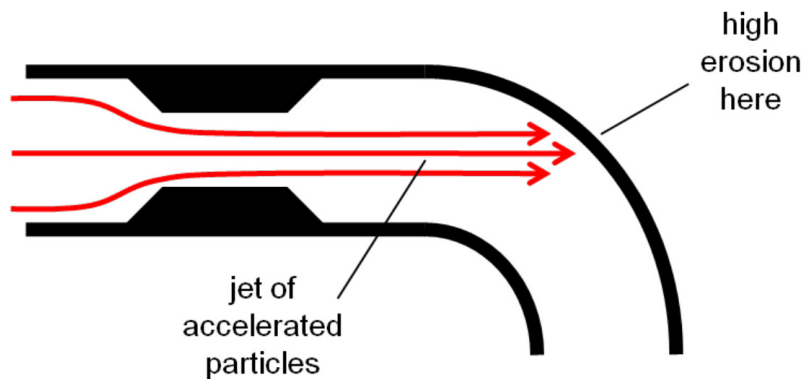


Figure 3: Illustration of How a Restriction Increases Erosion

5.1.3.2.3 Flow restrictions that reduce the pipe bore should be avoided whenever possible.

5.1.3.2.4 When practical, the separation between the restriction and any downstream elbow should be at least 10 pipe diameters (i.e. $S > 10D_1$ in Figure 4).

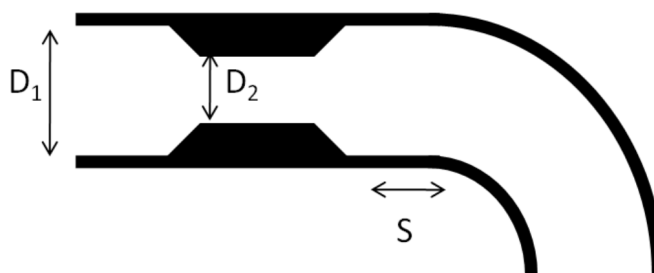


Figure 4: Restriction Dimensions

5.1.3.3 Taps

5.1.3.2.5 Taps are typically put into pipe walls to facilitate pressure and flow measurements. Erosion typically occurs on the downstream edge of the tap as illustrated in Figure 5. The impulse line joined to the main pipe often has thinner walls and under highly erosive conditions a scar at the edge of the tap can enlarge and penetrate the impulse line at its root.

5.1.3.2.6 The wall of the impulse line should be twice the thickness of the pipe wall where it joins the main pipe (see Figure 5: Illustration of Erosion in Wall Taps).

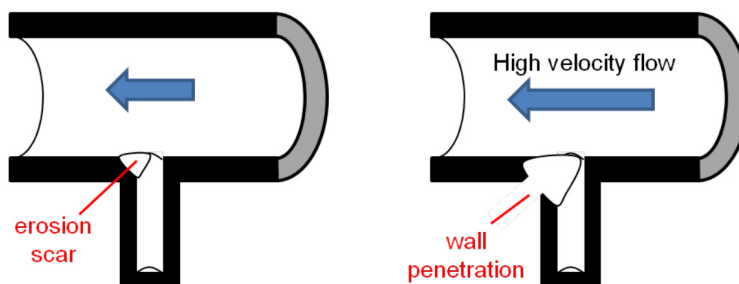


Figure 5: Illustration of Erosion in Wall Taps

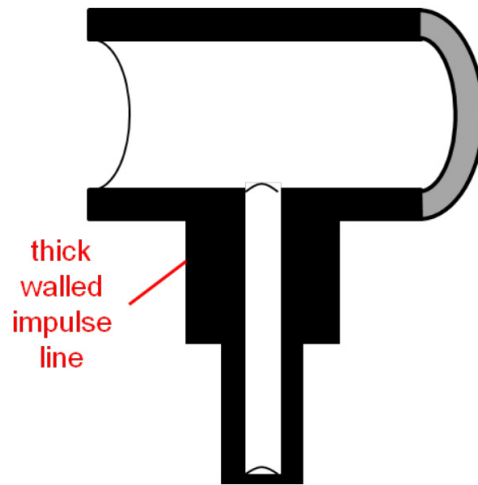


Figure 6: Increasing the Thickness of the Impulse Line Walls

5.1.3.4 Headers

5.1.3.4.1 Headers comprise a series of impacting tees, as illustrated in Figure 7. In this arrangement a continuous flow (Q_1) can be used to deflect particles entering from the side (Q_2 , Q_3 and Q_4) thus reducing erosion. However, this approach is only effective if the velocity of the Q_1 flow is at least equal to Q_2 .

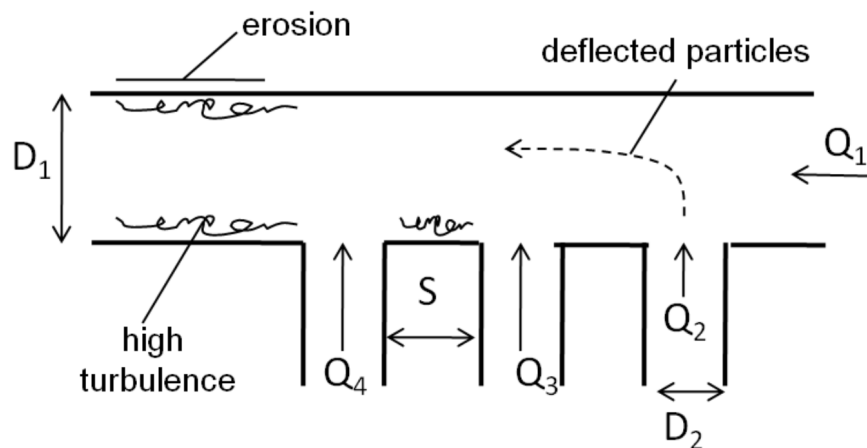


Figure 7: Flow in Header Configurations

5.1.3.4.2 Headers may be designed to have the in-flow entering at, as close as a glancing angle as possible; e.g., 45° as shown in the Figure 8.

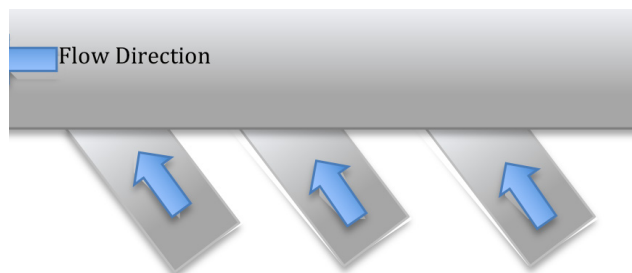


Figure 8: Possible Flow Header Configuration

5.1.3.4.3 Tees (where the flow impinges on the pipe wall opposite the entry to the tee and, depending on the flow properties and solid particles loading) can result in significant erosion damage. Direct impingement geometry should be avoided, as it is considered a worst case as it results in the erosion rate higher than any other configurations including 1D elbow.

5.1.3.4.4 High levels of turbulence between the inlet pipes and immediately downstream of the header can cause significant scouring erosion. The separation between the inlets (S) should be at least three inlet pipe diameters (i.e., $S > 3 D_2$).

5.1.3.5 Choke valves

5.1.3.5.1 The following list includes requirements and general guidance to minimize erosion damage in choke valves and associated pipework:

- a) Specific conditions are important and full details of fluids (e.g., gas/oil ratio, vapor pressure, solid particle content, pressure drops, and flow rates) for anticipated operating conditions shall be provided to the manufacturer.
- b) Choke valves are used for production streams, injection or combinations where production and injection alternates. The choke valves that see injection fluids or combination alternating injection and production fluids are more prone to have a significant corrosion component. This will affect the selection of materials to ensure adequate erosion resistance.
- c) Needle type chokes shall not be used if solid particles are present.
- d) Disk type designs shall not be used if solid particles are present. The flow downstream of a throttled valve takes the form of directional, high velocity jets that can rapidly erode pipework.
- e) Multipath designs:
 1. External sleeve or multiple stage/multiple flow path designs should be used. Plug and cage, external sleeve or multiple stage/multiple flow path designs should be used.
 2. Multipath designs can be more suitable in gas, two-phase, or flashing service. These employ different techniques to dissipate maximum energy in the trim area if highly erosion resistant materials are used.
- f) Choke valves appropriately sized shall be used and should be operated at no less than the vendor's recommendation of minimum opening in continuous operation, typically 20% open. If conditions change significantly during the service life, the trim should be changed accordingly. In case of need to use the choke valve at a different opening from the above guidance, the erosion SME should be contacted.
- g) Larger annular space (space between the cage and the choke body) should be used to allow for lower velocities in the valve body cavity on the inlet side, which will usually be unprotected carbon steel. A properly designed choke should use CFD modeling to optimize geometry.
- h) Any trim components that are subjected to high particle impact velocities shall be of erosion resistant material. The selection of materials for trim components shall take into account the potential for impact and corrosion as required to meet the needs of the specific application in addition to erosion. Standard trim materials in order of increasing erosion resistance include stainless steels, cobalt and nickel base hard-surfacing alloys, cemented tungsten carbides and ceramics. Additional information on materials for trim components is presented in Clause 5.1.4.2.
- i) To minimize wear on choke trim components, operating the choke at low fractions of the maximum choke capacity should be avoided. Guidance on choke operation to minimize trim wear is provided in DNVGL's Recommended Practice DNVGL-RP-0501 "Managing sand production and erosion."¹⁵
- j) Use of outlet port walls with erosion resistant wear sleeves or overlays may be used with some choke designs. Downstream of chokes, erosion (not protected as described above) may be avoided by fitting commercially available sacrificial sleeves (usually stainless steel) that are retained by the choke outlet flange joint and can be replaced as required.
- k) Straight piping should be extended immediately downstream of the choke valve outlets for a minimum of 6 nominal diameters. This also facilitates inspection for erosion damage caused by flow exiting the choke valve.

- l) The flow passage should be kept as much as practical within 10 nominal pipe diameters to 20 nominal pipe diameters downstream of a choke free of abrupt changes in direction to minimize erosion due to high velocity.

5.1.3.6 Isolation (block) valves

- 5.1.3.6.1** Only valves incorporating seats, balls, gates, etc. that have been coated with hard, erosion resistant material (e.g., tungsten carbide) shall be used as an erosion barrier.
- 5.1.3.6.2** Slab gate valves and trunnion mounted ball valves may be used for sandy service.
- 5.1.3.6.3** The following list includes requirement and general guidelines to help ensure that serious erosion problems are avoided (note that valves associated with produced water sand extraction plants usually require special consideration):
 1. The flow passage through an open valve should approximate, as closely as possible, the section of the adjoining pipe. Ball valves and through conduit gate valves are good examples of “full bore” valves.
 2. Reduced bore ball valves or reduced bore plug valves shall not be used for sandy service.
 3. Isolation valves shall not be used to regulate/control flow.
 4. Ball valves or gate valves with soft seats shall not be used in sandy service.
 5. Valve design should incorporate features to keep solid particles out of sensitive areas (e.g., seat pockets and trunnions).
 6. The ball, gate, and seat face should be coated with a hard material (e.g., tungsten carbide) to provide increased erosion and abrasion resistance.
- 5.1.3.6.4** In some isolation valve designs, the flow port is a slot whose cross-sectional area is similar to the pipe cross-sectional area. These are sold as being “full bore valves”. This type of valve should be avoided because it is considered as being a pipe restriction.

5.1.3.7 Pumps

- 5.1.3.7.1** When designing pumping equipment, fluid stream characteristics shall be included in the pump data sheet. This includes fluid chemical composition, solid particle size distribution and quantities.

5.1.4 Material selection to minimize erosion and erosion-corrosion

5.1.4.1 General

- 5.1.4.1.1** Common materials used in oil/gas production (e.g., carbon steel, 316 SS, 13%Cr steel, duplex stainless steel, Alloy 825, Alloy 625) do not have a high erosion resistance, and the erosion rate of these materials is quite similar. Therefore, corrosion resistant materials should not be used for increased erosion resistance. However, the use of corrosion resistant materials increases corrosion resistance, and modified 13% Cr or higher alloyed materials avoid the possibility of erosion and corrosion synergy.
- 5.1.4.1.2** Erosion resistant materials tend to be either very hard or very soft. Clearly, these two extremes function to reduce erosive wear through different mechanisms, but improved erosion resistance can result in both instances. Materials may be applied in either solid form or as coating.

5.1.4.2 Use of hard materials

- 5.1.4.2.1** Erosion resistance of materials varies widely as a result of local conditions (e.g., impact angle), but generally, the following materials have increasing erosion resistance in the order listed:
 1. Cobalt alloy 6
 2. Cobalt alloy 1
 3. Partially stabilized zirconia
 4. Tungsten carbide
 5. Erosion resistant refractories (category AP 50)
 6. Sintered silicon carbide
 7. Diamond

5.1.4.2.2 More detailed information about ceramics, carbides and diamond can be found in Annex B.

5.1.4.2.3 For these hard materials, and especially the cemented tungsten carbides, the following information is relevant:

1. This class of materials are typically very hard constituents bonded together with a matrix.
2. There is a relationship between bulk hardness and the matrix or binder content and the particle size of the hard constituent(s). As the particle size decreases and the binder contents decreases, the hardness increases.
3. Though erosion resistance generally increases with increasing hardness the mean free path between hard particles complicates prediction of performance only by hardness.
4. The mean free path between the hard particles is very important especially when considering fine erosive particle. In cemented carbides this has led to decreases in the hard particle size and decreases in binder contents.
5. The matrix represents the component that may be susceptible to corrosion and, therefore, erosion-corrosion. For example, in corrosive environments with cemented tungsten carbides, the cobalt binder phase is altered with the addition of chromium or nickel is substituted.
6. Toughness is almost always a variable that need to be assessed. If the toughness is not sufficient for the application, the risk is that the erosion resistant component will not provide the required erosion resistance because it has failed through fracture of the hard component(s).

5.1.4.3 Use of CRAs to avoid the corrosion element of erosion-corrosion

5.1.4.3.1 The corrosion element of erosion and corrosion threat can be avoided using CRAs, such as stainless steels (e.g., Super 13%Cr stainless steels, duplex stainless steel), nickel alloys (e.g., Alloy 625), and similar materials. 13% Cr steels can undergo synergistic erosion-corrosion in certain conditions.

5.2 Barriers for erosion threat in operations

5.2.1 In operations the main erosion barriers are listed below:

- Flow rate control
 - Reducing the production flow rate.
 - Well start up procedure.
 - Use of erosion probes tied into operational shut down logic.
 - Diagnostic analysis of differential flow conditions (Periodic stepping up and down of choke to monitor flow conditions envelope).
 - Online acoustic sand detectors associated with alarms.
- Sand exclusion, sand control, and sand removal
- Well clean up procedure

5.2.2 Production flow rate reduction according to procedure explained in Section 9 should be used as a barrier for erosion threat.

5.2.3 Well start up or bean up procedure is used to prevent or reduce the amount of sand produced. Erosion damage can happen very quickly, especially during fast well start up. In this case, an erosion monitoring system should be used to make sure that well start up procedure does not cause significant erosion damage.

5.2.4 Erosion probes should be tied into operational shut down logic to avoid significant erosion damage caused by unexpected high sand production rate.

5.2.5 Erosion and sand monitoring allow periodic stepping up and down of choke valve to identify the safe flow conditions envelope to avoid erosion damage.

5.2.6 Different techniques for sand removal including de-sanding cyclones, de-oiling cyclones, wellhead de-sanders and jet pumps may be used.

5.2.7 A combination of different erosion barriers should be used in operation to reduce the erosion threat.

Section 6: Monitoring

- 6.1** Monitoring devices are key to manage erosion and/or erosion-corrosion.
- 6.2** Very high erosion rates are possible when high flow rates are combined with high solid particles loading. This makes sand and erosion monitoring critical for safe and reliable operations.
- 6.3** Monitoring techniques for erosion management can be grouped as follows:
- Barrier monitoring. In this case monitoring techniques are used to assess the performance of the barriers put in place to mitigate erosion threat, e.g., acoustic sand detectors, flow rate control, sampling.
 - Erosion rate monitoring. The monitoring techniques are used to measure erosion rate directly. The measurement can be performed using an intrusive probe or sensors located on the outside of the equipment wall. Examples of erosion monitoring techniques are intrusive erosion probes (Section 7.1) and permanently installed monitoring (see Section 6.12).
- 6.4** Where sand production is a possibility and there is a credible threat of erosion, there should be at least one real-time, on-line sand or erosion monitoring system (e.g. using acoustic detectors, PIMs and/or intrusive erosion probes).
- 6.5** Monitoring systems are usually used for one of two scenarios:
1. Sand production is expected and needs to be managed.
 2. Sand production is not expected but could occur due to failure of preventive measure, e.g., failure of the sand control completion.
- 6.6** In the first case, the detection systems provide a warning if there is a change in sand production rates. The monitoring system can also be used to optimize fluid and sand flow rates for wells and facilities.
- 6.7** In the second case, monitoring systems are usually set-up to activate an alarm, which should be followed by measures to avoid erosion and other solid induced damages. An example of a measure to avoid erosion is choking down the well or even shutting it in.
- 6.8** Sand detection and erosion monitoring systems are the only way to provide assurance that the allowable sand rate is not exceeded.
- 6.9** The following is a list of erosion monitoring and sand detection techniques:
- 6.9.1** Erosion monitoring:
- Electrical Resistance (ER) probes
 - High sensitivity (thin elements)
 - Low sensitivity (thick elements)
 - Instrumented spools
 - Permanently Installed Monitoring (PIM)
 - Spot
 - Multi-spot/Local area
 - Remote area
 - Intrusive erosion tubes
- 6.9.2** Sand Monitoring
- Acoustic sand detection
 - Solid particles sampling
 - Density measurements gamma densitometer
- 6.10** ER erosion probes
- 6.10.1** Electrical resistance (ER) probes operate on the principle that the electrical resistance of a measurement element increases as its conductive cross-sectional area decreases as the result of corrosion, erosion or a combination of both. For erosion applications the measurement element material is usually a CRA, such that the corrosion contribution is negated. Only the metal loss caused by sand impingements on the probe elements is captured. The following are some important facts about ER erosion probes:
- High sensitivity to metal loss in the sub-micron range can be obtained.
 - Placement of probes plays a significant role in its effectiveness in detecting sand and evaluating erosion rate.

- They are not affected by noise from chokes or valve assemblies, however rapid change of temperature can adversely affect reading accuracy.
- The erosion rate measured on the probe can be different from the erosion rate occurring on the pipe wall.
- Do not use ER probes with wire elements for erosion monitoring.
- Use ER probes with CRA elements for erosion applications.

6.10.2 Installation of ER probes

- 6.10.2.1** Different manufacturers offer different configurations and designs of elements. Angled and flat-head probes can be installed in different locations within a pipe. Installation details, probe orientation and extension into the pipe, shall be provided by the supplier. Multi-element probes shall be positioned to extend across the pipe diameter (with the sensing elements oriented opposite the flow direction so that the flow impacts the sensing elements).
- 6.10.2.2** Intrusive erosion probes work better when there is a uniform distribution of the sand in the pipe section. For this purpose, intrusive probes should be installed horizontally across a vertically upwards flow path. The probe should be at least one pipe diameter after the bend on the outside of the bend. The longer the distance from the bend the better.
- 6.10.2.3** All intrusive probes should have a flanged access fitting. Sufficient clearance should be allowed to utilize the tool to insert and extract probes under pressure.
- 6.10.2.4** There have been cases of probe damage occurring from debris recovered during initial flowback of wells (since the probes extend into the flow path). To avoid damage during the well clean up, the intrusive probe may be inserted after the well clean-up has been completed.
- 6.10.2.5** Wake vortex shedding frequency of intrusive ER probes shall be assessed by the probe supplier to make sure that vibration caused by drag force of flow does not break the ER probe.
- 6.10.2.6** Subsea intrusive probe installations are not (currently) removable by remotely operated vehicle (ROV). Subsea probe locations are typically on a removable jumper, so that they can be replaced if the jumper is pulled out.

6.10.3 Calibration of intrusive erosion probes

- 6.10.3.1** Intrusive erosion probes are not usually calibrated in-situ. If any calibration is needed, it should be done based on the recommendation of probe vendor.
- 6.10.3.2** Deriving sand production rate from erosion probe response can be subject to significant error. However, whenever there are no other ways to evaluate the sand production, intrusive probes may be used. Adhering to location installation guidelines for erosion probes will also improve sand rate estimates. Any correlation can be “tuned” to improve accuracy over time using actual recovered sand.

6.11 Instrumented spools

- 6.11.1** There are a few instrumented spools available for metal loss measurements. These spools are of the same diameter as the pipe and made of the same pipe material. They work on the principle of electrical resistance measurement. The electrical resistance increases when the pipe wall is consumed by erosion or corrosion. Each spool is associated with a proprietary method of making measurements and calculation.
- 6.11.2** The instrumented spools have the benefit of covering a large area. High cost and the impossibility to distinguish erosion from corrosion wall loss are two disadvantages of the instrumented spools.

6.12 Permanently Installed Monitoring (PIM)

- 6.12.1** PIMs are non-intrusive permanently installed sensor systems that are used to detect and monitor material damage. PIMs provide a step-improvement in the accuracy, repeatability, and real-time wall thickness data. PIMs output can be read online and may be associated with alarms.
- 6.12.2** The deployment of permanent, online monitoring devices to detect erosion, can offer some advantages:
 - Reduce the need for frequent, conventional, routine manual inspections, where short inspection intervals are often prohibitive, particularly where access is difficult or restricted.
 - Better assessment of erosion rates with the potential to increase production rates without compromising the equipment integrity.

- Provide real-time wall thickness data when a velocity excursion event occurs resulting in wall loss and allowing proactive preventative and mitigative measures (operational or administrative) to be implemented before equipment is subjected to damage and/or loss of primary containment (LOPC).

6.12.3 PIMs, that are spot monitoring devices, can miss the erosion scar. Furthermore, changes in flow regime and rate can change the location of the erosion scar. Regular manual inspection should be used in the initial phase of PIM application to validate PIM positioning. These inspections should be repeated when there is a change in flow conditions. The position of the sensor may be easily modified in accordance with inspection results.

6.12.4 To improve PIM's erosion detection, a CFD simulation should be performed to determine the initial location of PIM sensors.

6.13 Intrusive erosion tubes

6.13.1 Intrusive erosion tubes (also called "pressure triggers" or "erosion alarms") have been used in the past. These are tubes, made of corrosion resistant material with known wall thickness, exposed to the flow stream. If a hole is caused by erosion in the tube, a pressure transducer senses the pressure change inside the tube. An alarm is usually associated with the pressure increase. These are sometimes installed in subsea trees. Two or more tubes with different wall thicknesses can be installed. Due to uncertainties associated with intrusive tubes, they are not considered sufficient as "on-line" erosion monitors. These probes are usually provided by the tree manufacturers.

6.13.2 The intrusive erosion tubes should not be used as erosion monitoring technique because it gives only one data point and cannot be reused unless replaced.

6.14 Acoustic sand detectors (ASD)

6.14.1 Acoustic sand detectors are non-intrusive sand monitoring systems that measure the noise generated by solid particles hitting the steel surface. They are usually connected to the control room and associated with alarms. For a detail description of their operation please refer to NACE International Publication 3T199, Techniques for monitoring corrosion and related parameters in field applications.¹⁶

6.14.2 In topsides installations sensors are typically strapped on the outside of the pipe, but there is a wide range of installation options for both subsea and topsides.

6.14.3 When the alarm is activated, operations shall evaluate the situation and take the necessary measures to reduce erosion and other threats associated with sand production. A procedure shall be developed with actions to be taken for each alarm level and when these actions need to be performed.

6.14.4 ASDs should be calibrated when used to measure solid particles production rate. The calibration involves injection of sand of predetermined quantity and size. Particle size representative of the sand produced or expected from the reservoir should be used. The details on the calibration procedure are supplied by the ASD vendor.

6.14.5 ASDs usually have upper and lower sensitivity limits relative to the amount of sand that they can detect.

6.14.6 No signal from acoustic sand monitoring technique does not mean that there is no sand in the system. It should be assumed that some solid particles are present unless alternative monitoring techniques, such as monitoring sand build up in separators or taking samples from the flow stream, confirm the absence of solid particles. Minimum detectable amount of solid particles depends on many factors including flow regime, sand size, etc. Oil dominated systems can be difficult to monitor using ASDs. There is no simple threshold solid particle concentration below which erosion will not occur. Even small amount of sand can cause erosion damage if fluid velocity is high.

6.14.7 ASD positioning

6.14.7.1 The capability of the ASDs to detect solid particles and to quantify solid particle production rate depends on the positioning of the ASD. ASDs should be installed in pipework in accordance with the following criteria:

- Downstream of 90-degree elbow or tee.
- Within 1-5 pipe diameters from the upstream elbow or tee.
- Outside of elbow.
- Not immediately adjacent to choke or pipe outlet to avoid interfering noise.

6.14.7.2 Figure 9 shows schematically where to install and not install ASDs.

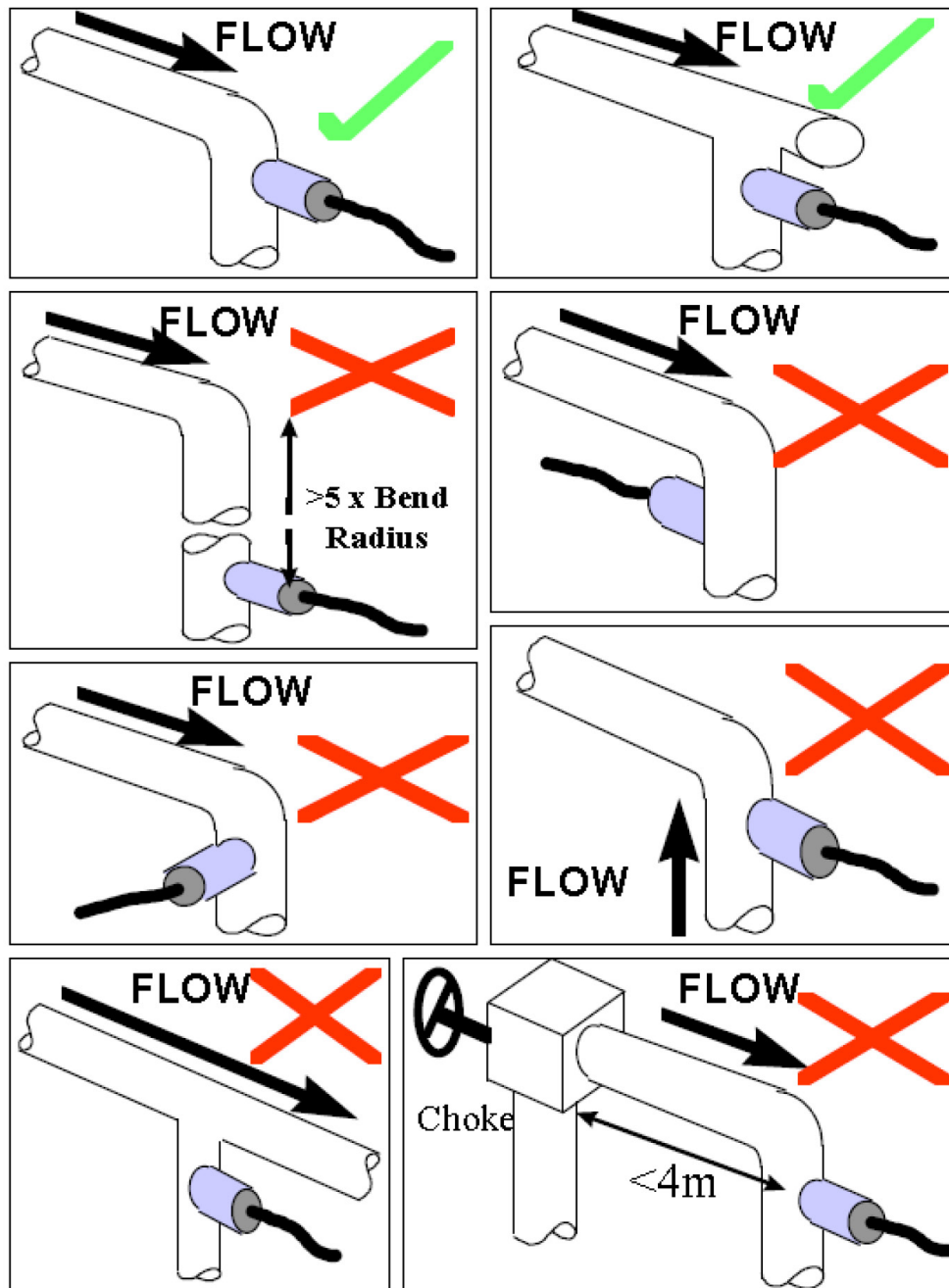


Figure 9: Acoustic Sand Detectors location guidelines

Section 7: Sampling

7.1 Sampling

- 7.1.1 Sampling (including sample analysis) is the most reliable method for obtaining solid particle characteristics, i.e., loading, size distribution, chemical composition, hardness, and density. It is also a useful method for detecting solid particles. Its reliability is based on the sampling point location along the pipeline network and also its o'clock position with respect to the cross sectional area. Solid particles sampling is frequently done at the same time and using the same equipment and procedures used for base sediments and water (BS&W) sampling. The analysis for solids usually follows a dedicated procedure which may include extraction (from oily phases for example), and unknown solids analysis using X-ray diffraction. Sometimes, a sample of larger volume is needed to obtain the minimum of solid particles needed for a complete characterization.

- 7.1.2** Sand can be collected from the liquid leg of the separator or sand handling system, however, sampling on oil, gas and water to resolve total concentration of solids is important. More frequent sampling will produce better information as sand production is often a transient event and sporadic sampling will possibly miss these events.
- 7.1.3** The sampling point location is critical for obtaining a representative sample of the solid particles contained in the stream. Experimental work at the University of Tulsa has shown that a representative sample can be obtained in a horizontal-to-vertical elbow, at one diameter distance and on the external part of the bend, on the vertical branch with up flow. The sample will be even more representative if it is taken at a longer distance from the bend. (point 1DO or above in the outer position, e.g., 2DO and 4DO, in Figure 10).

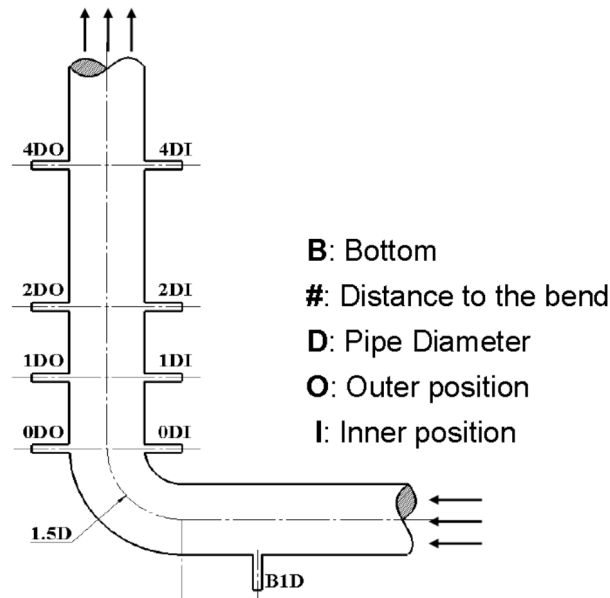


Figure 10: Schematic showing several possible sampling points.

- 7.1.4** The shape of solid particles can be modified as it flows in the process due to impact with hard surfaces. This should be considered when deciding the shape of solid particles.
- 7.2** Online erosion monitoring for offshore high value wells
- 7.2.1** Sand and erosion monitoring of subsea wells involves additional planning and design considerations. A significant amount of work has been done in the industry on sand monitoring for subsea applications as the well count has grown worldwide.
- 7.2.2** To have an efficient monitoring system at least one real-time, on-line monitor shall be in place near the subsea tree. An additional monitoring device should be installed on the surface as a back-up. Topside monitors may be placed on commingled risers, if the riser serves several wells. A more reliable system involves the use of ASD and erosion probe on the same line. An active sampling program at surface may be added to increase the system robustness.
- 7.2.3** PIMs can be installed downstream of choke valve and other locations that are vulnerable to erosion threat based on CFD erosion modeling. PIMs provide real time data for wall thickness, which can be connected to alarm system and provide warning in case of excess flow rate or sand production.

Section 8: Inspection

- 8.1** Performing inspections is a fundamental process to track system mechanical integrity and for erosion rate monitoring. This is particularly important when erosive-corrosive conditions exist. Along with erosion assessments, the information gathered from such inspection campaigns should be used as a proxy to determine the condition of the system elsewhere. This is particularly useful because it is not practical, and sometimes not even possible, to inspect all equipment or components that can be susceptible to erosion damage. Inspection programs should concentrate on inspecting those components deemed to be the most vulnerable to erosion damage.

- 8.2** The integrity management plan implemented for an asset usually prioritizes the necessary level of inspection and time-lines. However, when it is known that erosion or erosion-corrosion is a threat, the frequency of inspections should be increased and the integrity management plan adjusted accordingly. Field observations that may warrant the need for greater inspection frequency could be related to:
- Increased production rate
 - Increased solids loading
 - Increased corrosivity of fluids
 - The occurrence of impactful flow regimes such as slugging and annular flow
 - Initial put on production (POP) in new wells.
 - Hydraulically fractured wells immediately after POP.
 - New or old perforations are added in a well.
 - Acid stimulation of perforations.
 - Well bore clean out from sand and other solid particles using coil tubing.
 - Some other well works such as cast iron bridge plug (CIBP) milling, tubing swaps, cementing operations (squeeze), rig work overs, exempt (non-portable test separator) well, and test returns might require inspection notification.
- 8.3** If from the last inspection the piping design life is less than the remaining service life, the asset should consider erosion mitigation measures, de-rating the piping, replacing the piping or applying production rate adjustments (Section 9) to avoid erosion or erosion-corrosion.
- 8.4** Inspection Methods
- 8.4.1** The accuracy of wall loss measurement is dependent on the effectiveness of the inspection method selected as it relates to the equipment configuration and the environment in which it is deployed.
- 8.4.2** There are numerous inspection methods that can be used to inspect piping and pipe fittings.
- 8.5** Inspection Locations
- 8.5.1** The following guidance on locations should be followed considering the probability of erosion and erosion-corrosion damage:
- Prioritize the locations of the highest erosion threat (see 4.3)
 - Piping and/or pipe fittings immediately downstream of choke valves over their full circumference including 1st and 2nd second elbows where rebound erosion can occur.
 - Elbows and bends with a more careful coverage of the outside radius covering approximately from 30 degrees to 90 degrees of the outside radius.
 - Target tees covering the blocked end of the tee, the outlet branch of the tee, and a short length into the downstream pipe or pipe fitting.
 - Sections of straight piping immediately downstream of choke valves that can experience erosion damage.
 - Sections of contractions and expansions
- 8.5.2** One of the approaches used in inspection is to return to previously inspected locations and achieve repeatable wall thickness measurements. Often it is useful to imprint and maintain a reference grid over the pipe fitting for easy reference and data logging.
- 8.5.3** Referencing inspections to a predefined grid is particularly useful to assess expected and unexpected damage (e.g., the outside and inside radius of elbows or bends due to certain combinations of flow and geometrical obstructions or at tee connections where flow can directly impinge on surfaces perpendicular to the incoming flow direction). Often the apparent flow regime may dictate the locations (fitting) to target, for example liquid impingement due to annular flow or areas where churn flow or slugging are apparent.
- 8.6** Inspection Frequency
- 8.6.1** RBI approach as per API RP580 and RP581 in accordance with existing codes and regulations should be implemented. The inspection frequency shall be determined based on the erosion threat and may be modified based on the inspection results.
- 8.6.2** Inspection of high erosion threat locations may be necessary after a sand event.

Section 9: Production Rate Adjustment—Based on Erosion Threat

- 9.1** The procedure described below and represented in the flowchart in Figure 11 may be used for production rate adjustment based on erosion threat. Below, the steps in the flowchart are explained.
- 9.2** Erosion threat assessment
- 9.2.1** Erosion threat assessment is the first step. How to perform the erosion threat assessment is described in Section 4.
- 9.3** Identify the location of maximum erosion
- 9.3.1** Identifying the location of maximum erosion is part of the erosion threat assessment and is performed for each segment (see Section 4.3).
- 9.4** Determine $ER_{\text{acceptable}}$ & $FR_{\text{acceptable}}$
- 9.4.1** Calculate erosion rate using the erosion model (see Section 4.7).
- 9.4.2** The erosion and corrosion synergy can have a strong effect on carbon steel and 13% Cr stainless steels. Therefore, total wall loss for carbon steel and 13% Cr steel is equal to corrosion rate plus erosion rate plus synergistic effect between erosion and corrosion. For these materials, the acceptable erosion rate ($ER_{\text{acceptable}}$) is equal to the smallest value between the limit for erosion/corrosion synergy (e.g., 0.1 mm/yr) and remaining erosion allowance divided by remaining life of the equipment.
- 9.4.3** For other CRAs, that have no erosion/corrosion synergistic effect, the acceptable erosion rate is equal to remaining erosion allowance divided by the remaining life of the equipment.
- 9.4.4** The acceptable flow rate ($FR_{\text{acceptable}}$) is equal to the maximum flow rate for which the erosion rate is less or equal than the acceptable erosion rate. This $FR_{\text{acceptable}}$ should be calculated using the same erosion model used to calculate erosion rates in the threat assessment.
- 9.5** Is PIM installed in the location of max erosion?
- 9.5.1** If PIM is installed in the location of maximum erosion, then production can be continued at flow rates equal or smaller than acceptable measured flow rate. In this case (PIM installed), the acceptable erosion rate ($ER_{\text{acceptable}}$) is defined by PIM readings, not by model calculations. This gives the possibility to operations to increase flow rate until the acceptable flow rate is reached.
- 9.5.2** The PIM needs to have been validated to read reliably the wall thickness and have the accuracy needed.
- 9.5.3** Other techniques or combination of techniques that allow enough frequency and accuracy of wall thickness measurement can be used. It is the responsibility of the user to select the technique.
- 9.6** $FR (\text{flow rate}) \leq 0.9 FR_{\text{acceptable}}$
- 9.6.1** If PIM is not installed, production rate should be reduced to at least 90% of acceptable calculated flow rate. Regular inspections should be performed in the maximum erosion locations to make sure that erosion threat is managed properly.
- 9.6.2** An inspection program shall be developed to manage the erosion threat. Initially the frequency of inspection shall be high and should be reduced if the previous inspection shows no damage and the operating conditions remain the same.
- 9.6.3** Inspection should also be used for increasing production rate. Corrosion engineers or erosion SMEs need to be consulted in this case.
- 9.7** $ER_{\text{inspection}} < ER_{\text{acceptable}}$
- 9.7.1** If the erosion rate measured by inspection ($ER_{\text{inspection}}$) results are higher than the acceptable erosion rate ($ER_{\text{acceptable}}$), then the flow rate shall be reduced until the erosion rate measured by inspection becomes lower than the acceptable erosion rate. The corrosion engineer or the erosion SME shall assess the reason for higher erosion rates than expected.
- 9.7.2** If inspection results show erosion rates below acceptable erosion rate, the production may continue at the same flow rate. There is a possibility to increase the flow rate further. However, the erosion threat should be analyzed carefully and the erosion SME should be consulted before taking this step.

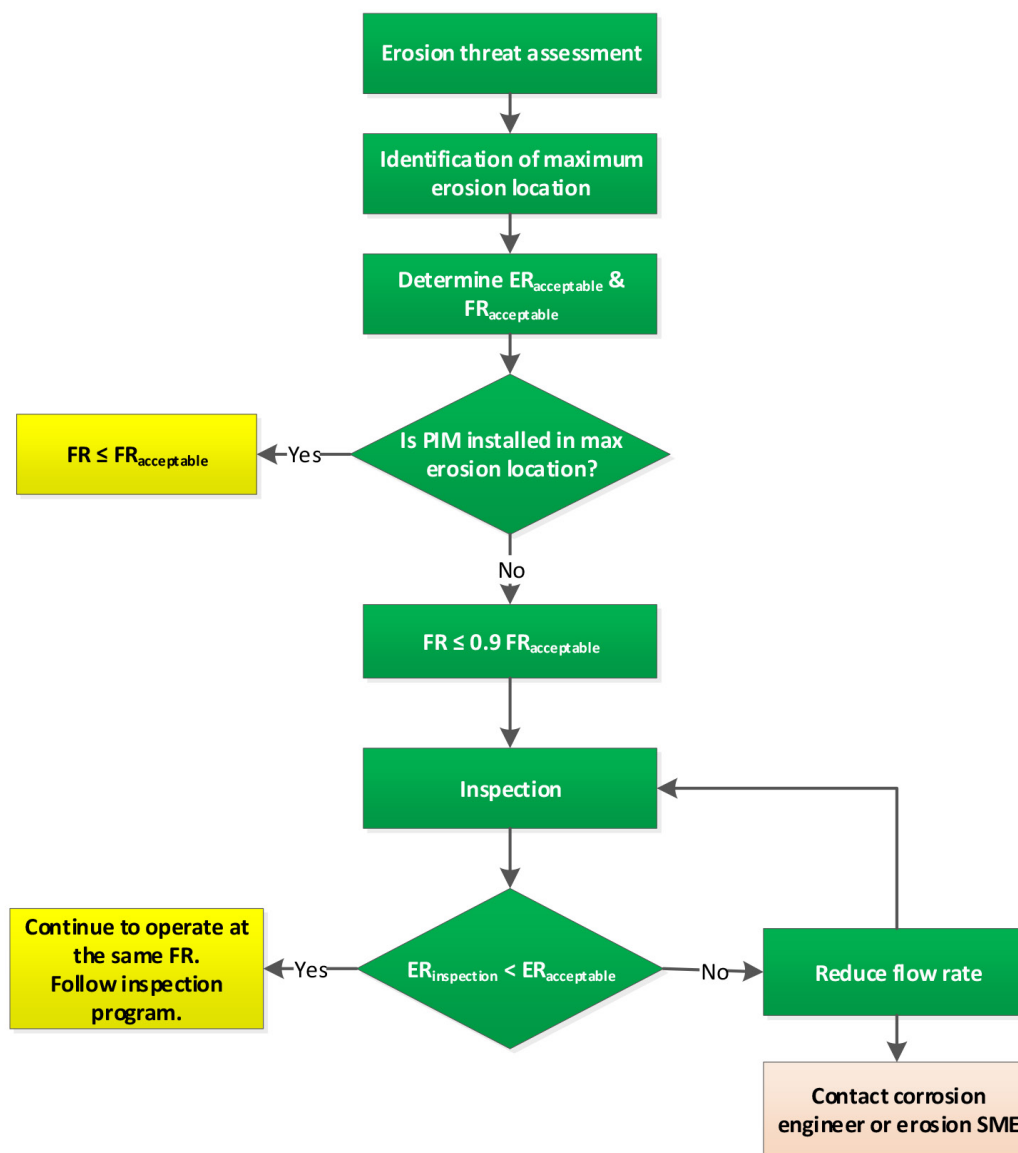


Figure 11: Production Rate Adjustment Flowchart

9.8 Contact erosion SMEs

9.8.1 Erosion SMEs shall be contacted when erosion threat assessment needs to be conducted outside of the limits of the erosion model. For example, conducting the erosion threat assessment for complex geometries such as expansion/contraction, valves or situations where upstream geometry affects flow pattern in downstream geometry.

9.8.2 Erosion SMEs should be also contacted to decide whether to conduct the CFD erosion analysis or laboratory study.

9.9 Risk assessment

9.9.1 The likelihood and the consequences of the erosion damage shall be assessed to evaluate the erosion risk.

9.10 Likelihood evaluation

9.10.1 To calculate the erosion likelihood, the results of the erosion rate calculations shall be combined with the effectiveness of the barriers put in place.

9.10.2 The following steps should be performed to calculate the erosion likelihood:

1. Calculate the remaining erosion allowance (EA).

$$EA = t_{\text{actual}} - t_{\text{required}} \quad (1)$$

Where

t_{actual} = the thickness measured in the given location

t_{required} = the thickness required for the function of the equipment (e.g., for pressure containment).

2. Calculate the erosion rate (ER) as described in Section 5.7 considering the barriers that have been implemented to reduce erosion threat. Take also into account any changes in future operation which would modify the erosion threat.
3. Determine the remaining life of the equipment (RL)

$$RL = EA/ER \quad (2)$$

9.11 Consequences evaluation

9.11.1 The determination of the consequences of erosion damage is outside the scope of this document. This needs to be assessed case-by-case involving a multidisciplinary team.

9.11.2 Typically, the multidisciplinary team should include representatives from:

- Process safety.
- Operations.
- Corrosion.
- Inspection.
- Production chemistry.
- Flow assurance.

9.11.3 Contributions from other disciplines (e.g., structures, wells, health, safety, and environment (HSE), materials and welding) should be required as warranted by the type of facility and equipment under consideration.

9.11.4 Periodic assessments to re-evaluate the erosion threat, update the risks, and revise the associated erosion management plan(s) should be performed.

Section 10: Performance Management

10.1 Key performance indicators (KPI)

- a. The following key performance indicators shall be used as a minimum to track the performance of the erosion management:
 1. Production deferrals caused by erosion.
 2. Number of loss of primary containment (LOPC) events caused by erosion.
- b. The above KPIs shall be captured quarterly as a minimum.

10.2 Corrective action plan

Corrective action plans shall be developed whenever the performance indicators do not meet the target values identified by the erosion management program.

10.3 Erosion management program review and improvement

An erosion management review shall be performed at least yearly and eventual improvements shall be implemented on a schedule compatible with the erosion risk.

10.4 Data and information management

10.4.1 Data management is a critical part of erosion management strategy. All information (including documents and data records) that is generated as a part of the erosion management program(s) shall be accessible to allow analysis and trending.

10.4.2 Online erosion data should be analyzed on a regular basis.

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Appendix A

Segmentation for Erosion Rate Assessment (Nonmandatory)

This appendix is considered nonmandatory, although it may contain mandatory language. It is intended only to provide supplementary information or guidance. The user of this standard is not required to follow, but may choose to follow, any or all of the provisions herein.

A1 Example of production system

- A1.1** The following figure shows an example of a production systems and different segments for erosion rate assessment. Segmentation is performed based on change in flow geometry, and flow/fluid properties. Change in solid particles content in the system also needs to be considered for segmentation. For example, solid particles content before and after separation are different.

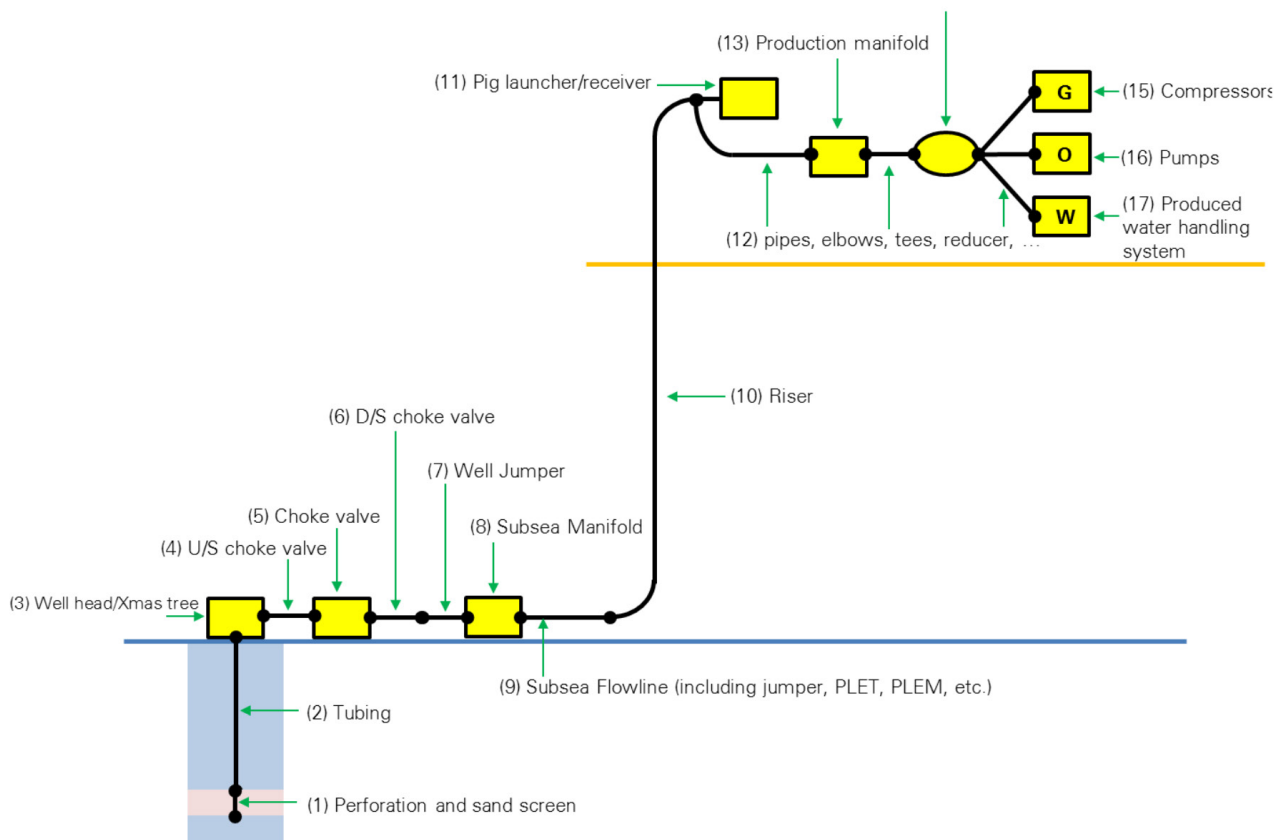


Figure A.1: Idealized Production System Segmentation for Erosion Assessment

Appendix B

Erosion Resistant Materials: Ceramics, Carbides and Diamond (Mandatory)

B1.1 Ceramics

B1.1.1 “Transformation toughened” ceramics, (e.g., zirconia) offer the benefits of high hardness, wear resistance, and corrosion resistance without the characteristic usual ceramic absolute brittleness.

B1.1.2 The erosion resistance of ceramics is extremely variable. Although in some instances, the variance in performance is due to differences in experimental procedures, more often it is related to the quality of the material tested. With high quality ceramic material, a 200 fold improvement in erosion resistance over carbon steel is achievable.

B1.2 Carbides

B1.2.1 Tungsten carbides are specified at critical locations instead of Cobalt based alloys, if optimum erosion or wear resistance is desired. Choke valves invariably use trim components manufactured from solid, sintered carbide.

B1.2.2 Carbide grain size has a significant effect on erosion resistance, such that fine grade carbide (< 1 µm [0.04 mils]) has approximately twice the erosion resistance of larger grade carbide (5 or 6 µm [0.20 or 0.24 mils]).

B1.2.3 Increased erosion resistance (due to fine grain size) is achieved at the expense of toughness. Therefore, sintered components need to be supported by ductile material.

Erosion resistance of sprayed carbides varies by a factor of 2 to 4, depending on the formulation and type of gun used. Generally, processes that minimize porosity give better results.

B1.2.4 Since carbide coatings are brittle, it must be demonstrated that, where such coatings are likely to be subject to high strain (e.g., on the seats of ball valves closing against high differential pressure), this can be accommodated without cracking of the carbide coating.

B1.3 Diamond

B1.3.1 Diamond has been shown to resist erosion many times better than even tungsten carbide.

B1.3.2 Diamond can be used in two forms:

- Polycrystalline (solid lumps).
- A thin coating applied by chemical vapor deposition (CVD).

B1.3.3 If a tungsten carbide substrate is used, the erosion resistance of CVD coatings can be spectacular. However, this technology is not yet commercially available, and its eventual cost will probably restrict the use of CVD coating to the most critical areas of a component (e.g., choke valve trim) and to applications for which replacement costs are very high (e.g., subsea).

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