Downhole metallurgy – overview of selection methodology for exploration and production wells

Tubular materials, as casing and tubing, are routinely selected first and thereby establish requirements for associated metallic accessories. Figure 1 summarises the selection process for exploration and production well tubulars. The underlying logic can be extended to accessories and other well types.

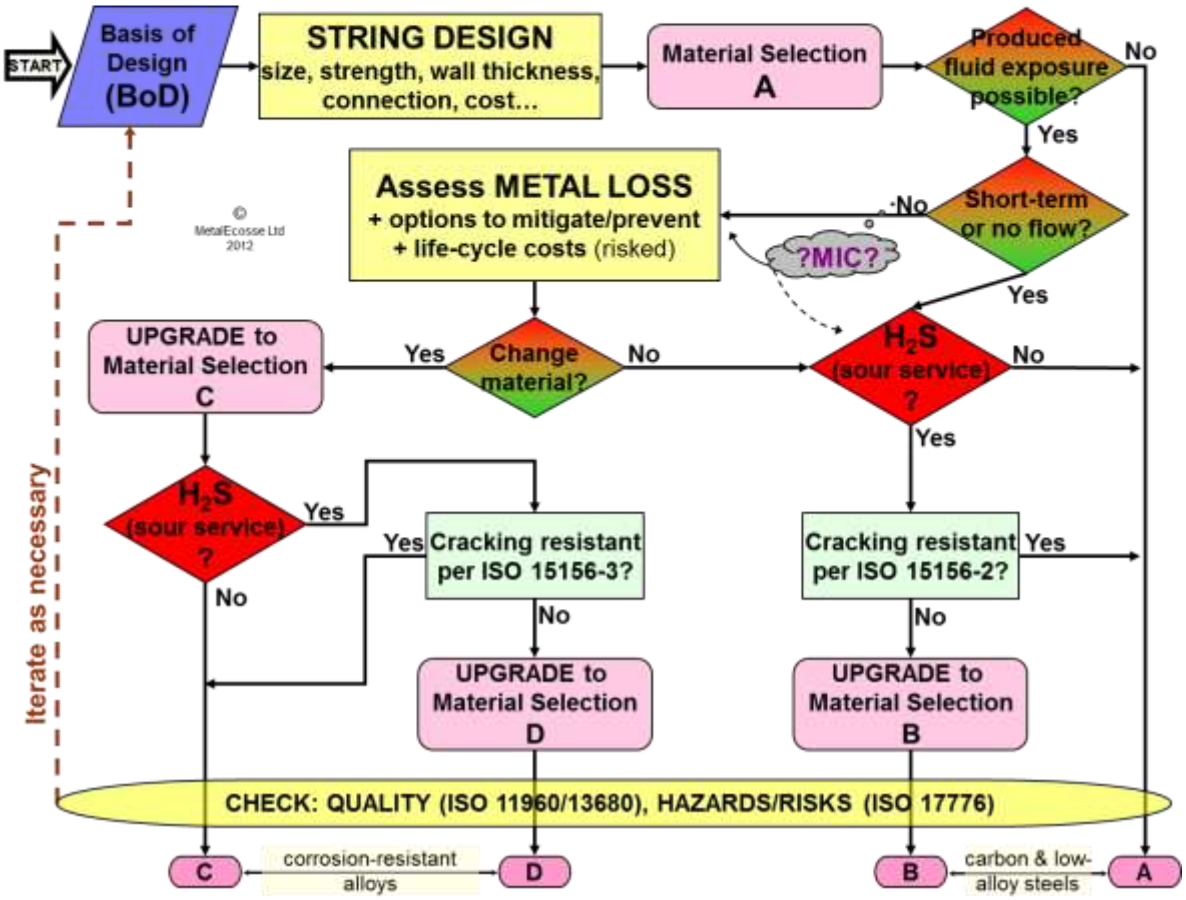

Figure 1: **Overview of selection methodology for exploration and production well tubulars exposed to natural (and near-natural) fluids.**
The chart is entered at the top, left. Alternative outcomes are identified A, B, C and D at the bottom. The logic can be extended to other well types by considering the potential for environmental cracking and metal-loss corrosion during exposure to each well fluid.
Note: The flowchart has been developed from a concept proposed by Daniel Loulergue of S&L Consulting.

Figure 2 identifies primary industry standards, etc that assist with use of the flowchart. Alternative sources, including local regulations and proprietary in-house documents, may be available and should be considered to extend the sources listed.

From Figure 1, the first task is to identify the lowest cost tubular material that is mechanically adequate for the required duty. The starting point is API/ISO grades of carbon and low-alloy steels [1]

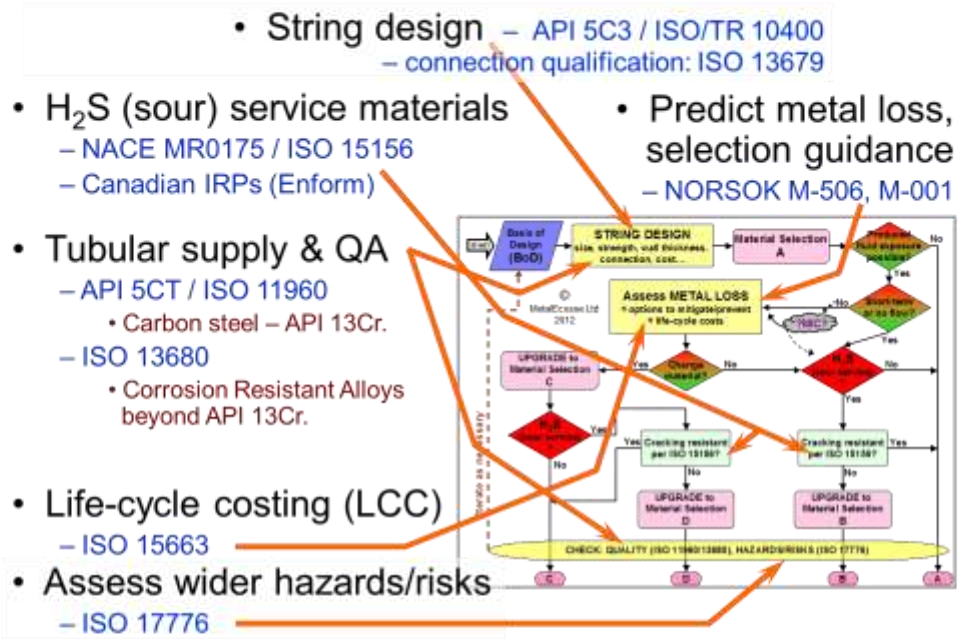

Figure 2: **Industry standards, etc that can be used in conjunction with the flowchart (Figure 1).**
For 'Wellhead and Christmas Tree Equipment' see: ISO 10423 / API 6A.

(commonly abbreviated to 'carbon steels') that offer adequate mechanical properties. For initial design purposes this means yield strength (or a related property). If produced fluid exposure is possible, a corrosion assessment is required. This may identify the need to consider corrosion mitigation and/or alternative materials. In order of increasing cost, the options are well established as:

1. API/ISO 'carbon steels' with adequate mechanical properties.
   a. Note: the toughness requirements of API 5CT / ISO 11960 are based on a minimum 'handling' temperature of minus-18ºC (0^{o}F). Enhanced toughness is required for lower temperatures.
2. 'Carbon steels', as above, restricted to grades that resist sulphide stress cracking (SSC) in sour (ie H_2S) service.
3. Mitigation of metal-loss corrosion by (eg) inhibitors, internal linings, ~3% Cr steels, etc.
4. Corrosion-resistant alloys (CRAs) that resist metal-loss corrosion starting with API/ISO L80 9Cr.
   a. API/ISO L80 9Cr is now little used as offering no advantage over API/ISO L80 13Cr.
   b. Specifications for API/ISO 9Cr and 13Cr tubulars are in API 5CT / ISO 11960 [1] those for higher CRA tubulars are in ISO 13680 [2].

A summary of tubular specifications and grades is given in Table 1; the general trend is for costs to increase from left to right across the table and downward within columns. NORSOK M-001 [3] provides guidance on the selection of metallic materials for tubulars and completion accessories by generic well type. The NORSOK guidance is usefully extended by information in NACE 08089 [4].

	CARBON STEELS	LOW-ALLOY STEELS	Corrosion Resistant Alloys (CRAs)				
			STAINLESS STEELS				NICKEL ALLOYS
			MARTENSITIC		DUPLEX	AUSTENITIC	
Manufacturing Standard	API 5CT / ISO 11960:2011			ISO 13680:2010 (%Cr-Ni-Mo designations)			
Grades (Sour service grades of carbon and low-alloy steels are shown **bold** - C110 is 'restricted')	**H40** **J55, K55** **M65**	N80-1, N80-Q **L80-1** **C90-1, T95-1** R95 **C110**, P110 Q125	L80-9Cr, L80-13Cr	Group 1 13-5-2 13-1-0	Group 2 22-5-3 25-7-3 25-7-4 26-6-3	Group 3 27-31-4 25-32-3 22-35-4	Group 4 21-42-3 22-50-7 25-50-6 20-54-9 22-52-11 15-60-16
SMYS (ksi)	40, 55, 65	80, 90, 95, 110, 125	80	80, 95, 110	(65, 75, 80, 90), 110, 125, 140	110, 125, 140	110, 125, 140
Condition	options per spec HF, N, N&T, Q&T		Q&T		Cold Hardened (solution annealed)		

ISO 11960:2011 changed C95 => R95, added C110

Duplex: austenitic/ferritic. SMYS: specified minimum yield strength (room temperature). ksi: 1000 lbf/in^2.
Condition: HF: hot finished; N: normalised; N&T: normalised & tempered; Q&T: quenched & tempered.
Seamless only: L80 9Cr, L80 13Cr, C90, T95, C110; otherwise seamless or 'electric welded'

Table 1: **Summary of standardised grades of downhole tubulars.**
ISO 11960:2011 was published on 16/6/2011, the corresponding 9th edition of API 5CT was published in July 2011 and became 'effective' at 1/1/2012. The status of the new C110 grade in NACE MR0175 / ISO 15156 remains to be established.

Note: In Table 1 and the text, CRAs are identified conventionally in accordance with (eg) NACE MR0175 / ISO 15156-1, NACE 1F92 and EFC publication #17. In ISO 10423 (API 6A) a CRA is more restrictively defined as a "non-ferrous based alloy in which any one or the sum of the specified amount of the elements titanium, nickel, cobalt, chromium and molybdenum exceeds 50% (mass fraction)".

Given adequate mechanical properties, selection is determined by two primary corrosion considerations:

1. Metal-loss corrosion that may occur as:
   a. general (quasi-uniform) corrosion of 'carbon steels' or;
   b. localised corrosion (as pitting and crevice corrosion) of CRAs.

2. Environmental cracking that may occur as:
   a. sulphide stress cracking (SSC) of 'carbon steels' and the lower CRAs or;
   b. stress corrosion cracking (SCC) of higher CRAs.

Because environmental cracking may occur rapidly, it is a primary requirement that materials be reliably resistant to cracking under all service conditions. Requirements for the prevention of cracking in H_2S-service are given in NACE MR0175 / ISO 15156 [5]. Additionally, CRAs are selected to be fully resistant to metal-loss corrosion.

For CRAs, NACE/ISO [5] identifies the primary parameters that control environmental cracking as:

i) material type, condition, etc; ii) service temperature; iii) H_2S partial pressure;

iv) chloride (in water phase); v) *in situ* water pH;

vi) the presence/absence of elemental sulphur (that may be liquid or solid).

The water pH is determined by the produced water composition and acid-gas partial pressures.

a. The water analysis should include carboxylic acids (particularly acetic, ideally formic (methanoic) through caproic (hexanoic), ie C_1 - C_6).

b. The above do not account for microbiological activity that can create local corrosive conditions, hence MIC (microbiologically influenced corrosion); these are beyond the scope of this overview.

The above parameters also control metal-loss corrosion of CRAs, and with minor differences, metal-loss corrosion and environmental cracking of ‘carbon steels’. They are therefore the primary, and essential, inputs to the metallurgy selection process. Routinely there are two cases to consider.

Produced water source	Gas wells	Oil wells
Condensed water (from gas)	Early life	
Formation water	Later life	Early life
Injection water (breakthrough)		Later life

Formation water produced by gas wells may be concentrated by evaporation of water into the gas phase. This is most likely deep in a well and may cause concentration of dissolved solids, super-saturation and deposition of solids. Local conditions that result are difficult to define.

Condensate wells may ‘follow’ either category above. Wells perforated ‘high’ in the formation to exploit gas, are likely to have ‘gas well’ characteristics; wells perforated deep to maximise liquid production, are likely to have ‘oil well’ characteristics (excepting injection-water breakthrough).

The ‘worst-case’ temperatures for which metal loss and environmental cracking require assessment vary as summarised in Table 2.

Material	Metal loss	SSC	SSC/SCC	SCC
Carbon & low-alloy steels	varies	Ambient (room) temperature		
Martensitic SS (eg API 13Cr)	maximum service temperature			
Super-martensitic SS (eg super-13Cr)				*maximum service temperature
22%Cr duplex SS			~90°C	
25%Cr super-duplex SS			~120°C	
Super-austenitic SS (eg 28%Cr)				
Nickel alloys				
SS = stainless steel	*as precaution for super-martensitic and duplex stainless steels			

Table 2: Summary of primary temperatures for assessment of resistance to metal-loss corrosion and environmental cracking.
(Normally, there is no requirement in ‘empty’ cells).

Because 'carbon steels' can be specified to resist environmental cracking (as SSC), it is metal-loss considerations that may require use of corrosion mitigation measures or CRAs. Predicting metal-loss for 'carbon steels' is complex and insufficiently developed to allow the reliable prediction of completion lives even when service conditions are fully defined. Metal-loss assessments therefore have to be regarded as indicative only and used to assess the likelihood of premature failures. The consequences of such failures should be identified to determine if mitigation methods, or CRAs, are justified; the options are summarised in Table 3.

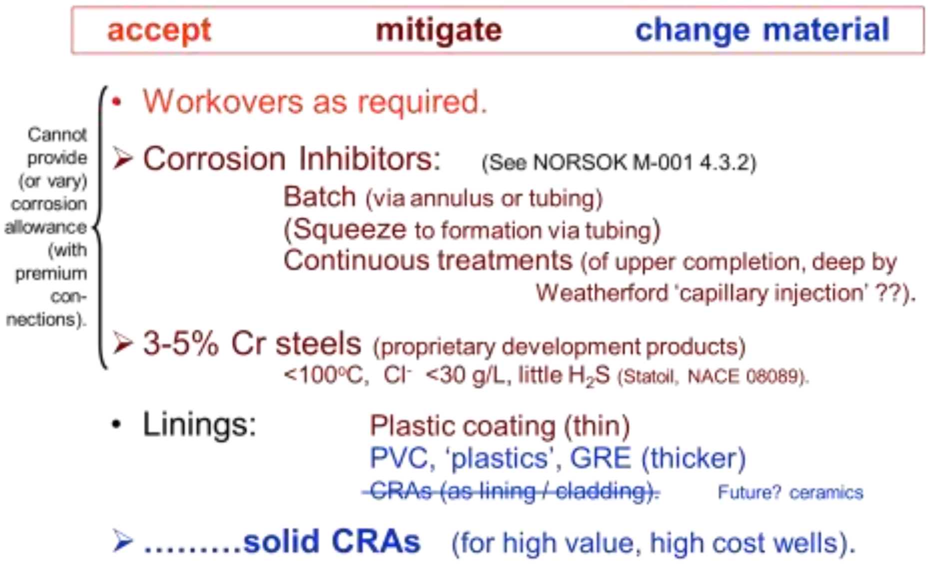

Table 3: **Options for managing metal-loss**
CRA linings and cladding have been proposed but no commercial product is yet available – hence the 'strikeout'.

The 'risk' and economics of alternative materials can then be compared using (eg) ISO methodologies. Failure 'risk' can be evaluated as likelihood*consequence using ISO 17776 [6] and life-cycle costs can be compared in accordance with ISO 15663 [7].

- For life-cycle costing, the use of 'high' discount factors that include 'project risk' is inappropriate for assessing workover costs after projects achieve 'discounted payout'. Such factors favour future workovers that may not be justified when they occur – see (eg) SPE 24651 [8].

It follows from this that the selection of downhole materials is not 'deterministic' and not only a 'technical' exercise. Risk assessment and economic analysis are also required even if these are not done quantitatively.

As stated at the outset, primary tubular materials are routinely selected first and thereby establish requirements for associated metallic accessories. As these may have a significant influence on overall costs, they should be included in life-cycle costings. Table 4 summarises the primary options for those parts of conventional accessories that are required to 'match' the corrosion resistance and strength of associated tubulars.

ISO / GROUP	Type	ISO category %Cr-Ni-Mo	Accessory options
ISO 11960	Carbon & low-alloy steels		Match or CRA from below
ISO 11960 ISO 11960	L80 9Cr L80 13Cr		Match or 13%Cr Match
ISO 13680 1	Martensitic Martensitic/ferritic	13-5-2 13-1-0	Match, 13-5-2 or Ni alloy
2	Duplex austenitic/ferritic (stainless steels)	22-5-3 25-7-3 25-7-4 26-6-3	(SA: match) CW: AH Ni alloy
3	Austenitic Fe based (stainless steels)	27-31-4 25-32-3 22-35-4	AH Ni alloy
4	Austenitic Ni based (nickel alloys)	21-42-3 22-50-7 25-50-6 20-54-9 22-52-11 15-60-16	AH Ni alloy Difficult to fully match

SA: solution annealed; CW: cold worked; AH: age (or precipitation) hardening.

Table 4: **Primary options for parts of conventional accessories that are required to 'match' the corrosion resistance and strength of associated tubulars.**

References

1 ISO 11960:2011: "Petroleum and natural gas industries - Steel pipes for use as casing or tubing for wells". (Also published as: API Specification 5CT, Specification for Casing and Tubing, 9th Edition).

2 ISO 13680:2010: "Petroleum and natural gas industries - Corrosion-resistant alloy seamless tubes for use as casing, tubing and coupling stock - Technical delivery conditions".

3 NORSOK Standard M-001: "Materials selection". Rev 4, August 2004. www.standard.no/petroleum.

4 Scoppio, L; Nice, P I: "Material selection for turnaround wells an evaluation of the impact upon downhole materials when mixing produced water and seawater". NACE Corrosion 2008, conference paper #08089.

5 NACE MR0175 / ISO 15156: "Petroleum and natural gas industries - Materials for use in H_2S-containing environments in oil and gas production". In three parts, published: ISO 10/2009; NACE 12/2010.

6 ISO 17776:2000: "Petroleum and natural gas industries – Offshore production installations – Guidelines on tools and techniques for hazard identification and risk assessment".

7 ISO 15663: "Petroleum and natural gas industries - Life-cycle costing". (In three parts published 2000 - 2001).

8 Campbell, J M; Campbell, John M; Campbell, R A: "Economic shortsightedness: one cause and cure". SPE 24651 (1992).