Downhole Metallurgy
escalating selection challenges

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Welding & Joining Society
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## Tubular usage - examples - TONNES

Range: 600 ~ 2,000 tonnes

<table>
<thead>
<tr>
<th></th>
<th>CASING Non-flow wetted</th>
<th>TUBING &amp; LINER Flow-wetted</th>
<th>TOTAL tonnes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clyde A01</td>
<td>760</td>
<td>147 (16%)</td>
<td>907</td>
</tr>
<tr>
<td>14,420 ft</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gyda A21</td>
<td>1,320</td>
<td>208 (14%)</td>
<td>1,528</td>
</tr>
<tr>
<td>26,597 ft</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Erskine W4</td>
<td>1,594</td>
<td>121 (7%)</td>
<td>1,715</td>
</tr>
<tr>
<td>18040 ft</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Remedial additions to original: 226
### API / ISO CASING & TUBING summary

<table>
<thead>
<tr>
<th>MANUFACTURING STANDARD</th>
<th>API 5CT / ISO 11960:2011</th>
<th>ISO 13680:2010 (%Cr-Ni-Mo designations)</th>
</tr>
</thead>
</table>

- **SMYS (ksi)**: 40, 55, 65, 80, 90, 95, 110, 125, 80, 80, 95, 110, 125, 110, 125, 140, 110, 125, 140

- **Condition**: Cold Hardened (solution annealed)
  - HF: hot finished; N: normalised; N&T: normalised & tempered; Q&T: quenched & tempered.

- **Duplex**: austenitic/ferritic
- **SMYS**: specified minimum yield strength (room temperature)
- **ksi**: 1000 lbf/in²

**Not listed**: C75, P105, V140/150, ~3%Cr, 316ss, MP35N, Ti alloys!
<table>
<thead>
<tr>
<th>Group</th>
<th>Grade (ksi)</th>
<th>Type</th>
<th>SMYS MPa</th>
<th>SMYS comparisons</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>H40</td>
<td></td>
<td>276</td>
<td>35 ksi - ASTM A106 B - process pipework</td>
</tr>
<tr>
<td></td>
<td>J55</td>
<td></td>
<td>379</td>
<td>51.5 ksi - BS 4360 50D - structural steel</td>
</tr>
<tr>
<td></td>
<td>K55</td>
<td></td>
<td>552</td>
<td>65 ksi - API 5L X65 - linepipe</td>
</tr>
<tr>
<td></td>
<td>N80 1</td>
<td></td>
<td>552</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N80 Q</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>M65</td>
<td>1</td>
<td>448</td>
<td>80 ksi - X80 on-land gas pipelines</td>
</tr>
<tr>
<td></td>
<td>L80 1</td>
<td></td>
<td>552</td>
<td>- ASTM B7M, L7M - fasteners</td>
</tr>
<tr>
<td></td>
<td>C90 1</td>
<td></td>
<td>621</td>
<td>84 ksi - R4 - anchor chain</td>
</tr>
<tr>
<td></td>
<td>C90 2</td>
<td></td>
<td>621</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C95 / R95</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T95 1</td>
<td></td>
<td>655</td>
<td>102 ksi - R5 - anchor chain</td>
</tr>
<tr>
<td></td>
<td>T95 2</td>
<td></td>
<td>655</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C110</td>
<td></td>
<td>758</td>
<td>105 ksi - ASTM B7, L7 - fasteners</td>
</tr>
<tr>
<td>3</td>
<td>P110</td>
<td></td>
<td>758</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Q125 1</td>
<td></td>
<td>862</td>
<td>210 ksi - HPHT xtree actuator springs</td>
</tr>
<tr>
<td></td>
<td>Q125 2, 3, 4</td>
<td></td>
<td></td>
<td>GIPS: 245 – 265 ksi, XXGIPS: 315 – 345 ksi</td>
</tr>
</tbody>
</table>

Carbon equivalent (for weldability) C + Mn + Cu+Ni + Cr+Mo+V
\[
\begin{align*}
C &= 6 \\
Mn &= 15 \\
Cu+Ni &= 5 \\
Cr+Mo+V &= \text{variable}
\end{align*}
\]
Sources of downhole water

**Oil wells**

1. Water wetting at all depths (for high water cut).
2. Chlorides (may vary).
3. Bicarbonate ($\text{HCO}_3^-$) dissolved in water buffers $\text{CO}_2$ - pH↑.
   pH usually >4.5

**Gas wells**

Water condenses from vapour as it cools

**Condensed water**

1. Wetting increases towards surface
   - low chloride.
2. No bicarbonate buffer - low pH. pH usually >3.5

LIQUID WATER with salts as

- Formation water
- Injection water breakthrough
- Aquifer water

Early Life: water (mostly) as vapour in gas. (Potential for evaporative scaling).

Late life: as for oil well.
CO$_2$ / H$_2$S metal-loss regimes

As proposed by Pots et al: NACE Corrosion 2002 paper 235 (#02235)
CRA options (Schaeffler diagram)
Structures of steels fast cooled from 1050°C

Nickel Equivalent
\[%Ni + 30\times\%C + 0.5\times\%Mn\]

Chromium Equivalent
\[%Cr + %Mo + 1.5\times%Si + 0.5\times%Nb\]

Key:
- a: L80-1
- b: L80-13Cr
- c: super-13Cr
- d: 22Cr DSS
- e: super-DSS
- f: 27-31-4, 25-32-3

‘the old days’
304ss
316ss

http://www.gowelding.com/met/diss.html
# NACE/ISO: controlling parameters (CRAs)
(to prevent environmental cracking as SSC &/or SCC)

**Table A.19 — Environmental and materials limits for martensitic stainless steels used as downhole tubular components and for packers and other subsurface equipment**

<table>
<thead>
<tr>
<th>Specification/Individual alloy UNS Number</th>
<th>Temperature</th>
<th>Partial pressure $H_2S, pH_2S$</th>
<th>Chloride conc.</th>
<th>pH</th>
<th>Sulfur-resistant?</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO 11960 L-80 Type 13 Cr. S41426, S42500</td>
<td>See remarks</td>
<td>10 (1,5)</td>
<td>See remarks</td>
<td>$\geq 3.5$</td>
<td>NDS$^a$</td>
<td>Any combinations of temperature and chloride concentration occurring in production environments are acceptable.</td>
</tr>
<tr>
<td>S41429</td>
<td>See remarks</td>
<td>10 (1,5)</td>
<td>See remarks</td>
<td>$\geq 4.5$</td>
<td>NDS$^a$</td>
<td></td>
</tr>
</tbody>
</table>

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**Environment**

- **pH** from $pCO_2$, $pH_2S$, water composition.
- (Oxygen-free!)
- *~8 primary environmental parameters control cracking…*

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**Material**

- Composition, strength, condition.
- Strength determines max local tensile stress. (Metals yield!)

---

NDS: no data submitted
CRAs: No metal loss, No cracking

governing temperatures for generic materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Metal loss</th>
<th>SSC</th>
<th>SSC/SCC</th>
<th>SCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon &amp; low-alloy steels</td>
<td>varies</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Martensitic SS (eg API 13Cr)</td>
<td>maximum</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Super-martensitic SS (eg super-13Cr)</td>
<td>service</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22%Cr duplex SS</td>
<td></td>
<td></td>
<td>~90°C</td>
<td>*maximum service temperature</td>
</tr>
<tr>
<td>25%Cr super-duplex SS</td>
<td></td>
<td></td>
<td>~120°C</td>
<td></td>
</tr>
<tr>
<td>Super-austenitic SS (eg 28%Cr)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nickel alloys</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

SS = stainless steel

*as precaution for super-martensitic and duplex stainless steels

**Primary cases:**

**Oil production:** formation water (then) breakthrough injection water

**Gas production:** condensed water (then) formation water
Casing with HPHT++ terminology

30” conductor

20” surface casing

13 3/8” casing

9 5/8” prod casing

7” production liner

TD (Total Depth)

Packer fluid

HPHT:
10,000 – 15,000 psi, 300 - 350°F

Extreme HPHT
15,000 – 20,000 psi, 350 – 400°F

Ultra HPHT
>20,000 psi, >400°F

Grade SMYS (ksi)  MPa
H40 276
J55 379
K55
N80-1 552
N80-Q
M65 448
L80-1 552
C90 621
C95 / R95
T95 655
C110 758
P110 758
Q125 862
HPHT & beyond – definitions
(JPT Jan 2011 p26)
Fig. 3: SMC110 SSC susceptibility to material Yield Strength and applied threshold stress. NACE Method A, solution A, 25 deg.C.
TUBULARS for Exploration & Production wells – NATURAL (& similar) FLUIDS

START

Basis of Design (BoD)

STRING DESIGN
size, strength, wall thickness, connection, cost…

Material Selection

Produced fluid exposure possible?

Yes

Short-term or no flow?

Yes

H₂S (sour service)?

Yes

Cracking resistant per ISO 15156-3?

Yes

Cracking resistant per ISO 15156-2?

Yes

UPGRADE to Material Selection B

No

UPGRADE to Material Selection D

No

UPGRADE to Material Selection C

No

Assess METAL LOSS
+ options to mitigate/prevent + life-cycle costs (risked)

Change material?

Yes

H₂S (sour service)?

No

No

CHECK: QUALITY (ISO 11960/13680), HAZARDS/RISKS (ISO 17776)

C corrosion-resistant alloys

D carbon & low-alloy steels

A