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ICORR 2023

ADDRESSING HYDROGEN PIPELINE REPURPOSING SAFELY & ECONOMICALLY

Dr Daniel Sandana, EUR Ing, PhD, MSc

- Introduction
- Challenges
- Grades – an adequate metric for materials performance in H_2 ?
- Repurposing strategies – if not Grades – then what?
- Conclusions & roadmap

Introduction

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We need H2

to meet

Paris Agreement

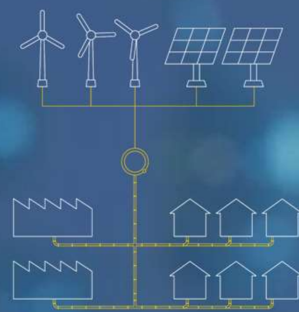
50-80%

consist of

repurposed

Existing

natural gas grids



13% to 15%

of Energy Mix will be

H2 and Ammonia

Heavy Industry & Long Transportation

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The Role of hydrogen in the energy transition

Lightest and most abundant
Hydrogen is the first element in the periodic table. It is the lightest, most abundant and one of the oldest chemical elements in the universe.

Never alone
On earth, hydrogen is found in more complex molecules, such as water or hydrocarbons. To be used in its pure form, it has to be extracted.

High energy density
Hydrogen has the highest energy content of any common fuel by weight.

Can be produced without a carbon footprint
through electrolysis or SMR + CCS

Can be transported over long distances,
allowing the distribution across regions.

Can be used as a buffer
to increase system resilience.

Produces clean power and heat
for transport and stationary applications.

Required as a clean feedstock
in industry when recycling captured CO_2.

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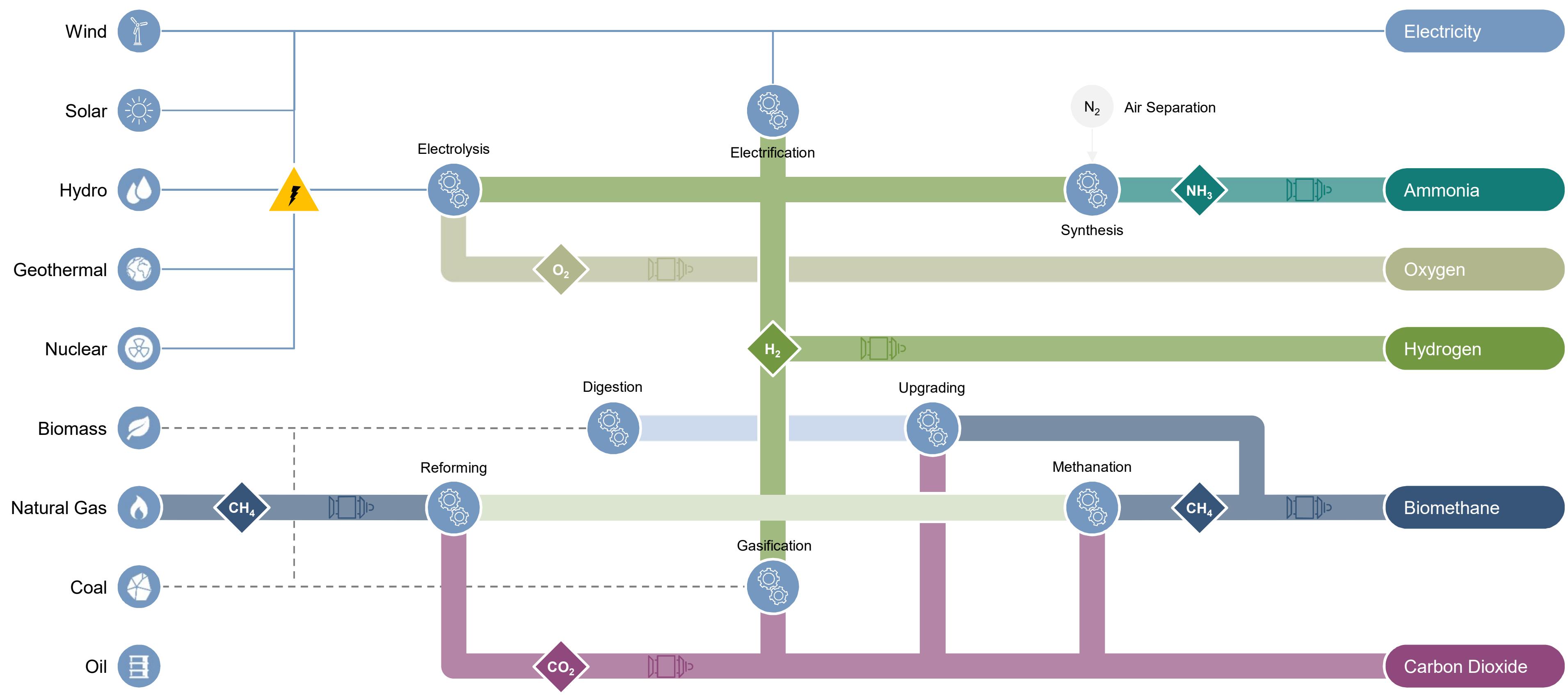
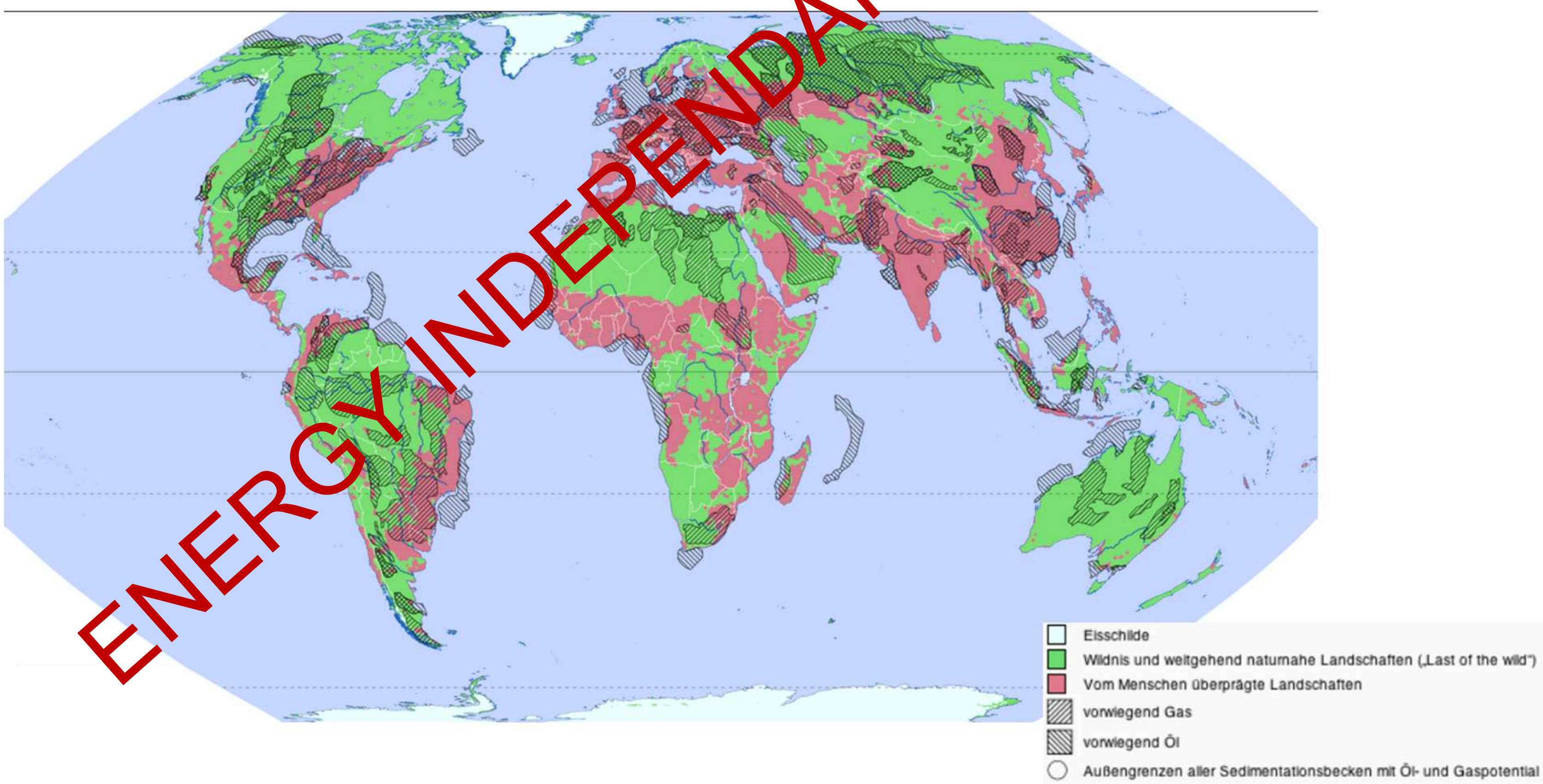
The Role of hydrogen in the energy transition



The Role of hydrogen in the energy transition

Hydrocarbon distribution



Hydrogen Infrastructure

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Approximately

1621 miles/ 2608 km

of Hydrogen Pipelines

are currently operated in the

United States

"Reference: Energy of the Future? Sustainable Mobility through Fuel Cells and H2" Shell Hydrogen Study. Page 26

Hydrogen Infrastructure

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Approximately

993 miles/ 1598 km

of Hydrogen Pipelines

are currently operated **in**

Europe

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>750

Hydrogen Projects in

Europe

53,000 km

pan-European Hydrogen Pipelines by 2040

28

European countries covered

>60%

Thereof consist of repurposed existing natural gas grids

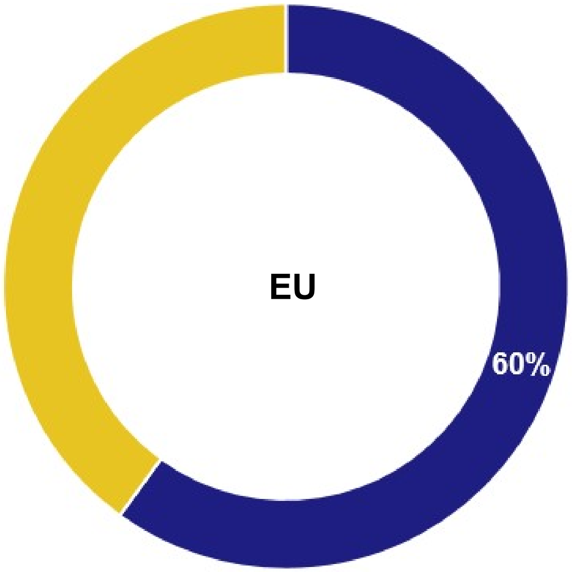
eferences:

hb, European Hydrogen Backbone, A European Hydrogen Infrastructure Vision Covering 28 Countries, April 2022;

uropean Commission website, https://single-market-economy.ec.europa.eu/industry/strategy/industrial-alliances/european-clean-hydrogen-alliance_en

Repurposing Natural Gas Pipelines

Role of pipeline Repurposing



H_2 Deployment at an industrial scale requires pipelines

Repurposed NG pipelines ~10-35% of new construction costs

Repurposing in EU … € 0.2 million to € 0.6 million / km

Cost / permit considerations ➡ >50% of H_2 pipelines globally will be repurposed from NG pipelines

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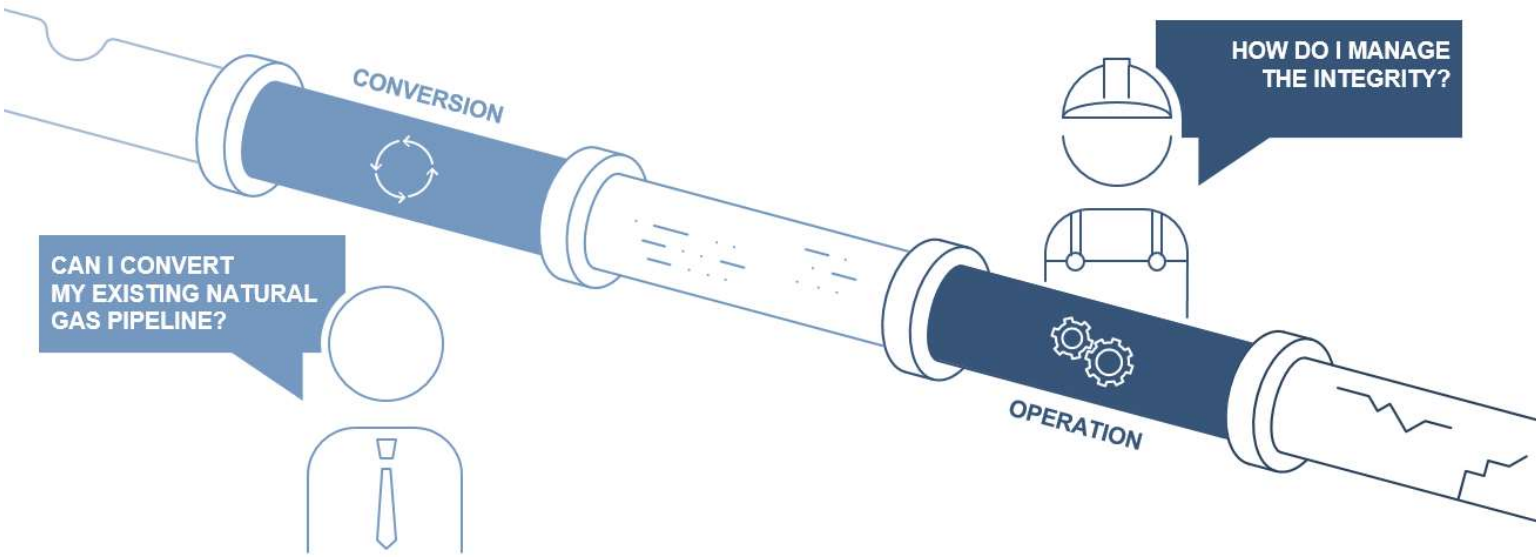
Repurposing Natural Gas Pipelines

Managing repurposing safely



- *Sandana D et al., Safe repurposing of vintage pipelines in North America, IPC 2022*
- *Safely Managing the Transition of Pipelines to H_2, E.-Peppler M et al. World H_2 congress 2021*
- *Existing pipeline materials and the transition to hydrogen, Gallon N et al., PTC 2021*

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Challenges

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REPURPOSING NATURAL GAS PIPELINES

Demonstrating the existing pipelines will remain fit-for-service under the new service

- **The process requires the documentation of engineering inputs in order to inform the decision-making process** for (i) the suitability to conversion, or if deemed necessary, for (ii) the development of practical economic rehabilitation and mitigation measures to achieve safe conversion.
- The **key engineering inputs** can be summarised as follows:
  - ✓ Identify Threats & Pipeline condition (baseline) e.g. vs. cracks.
  - ✓ Have an understanding of material ‘DNA’ & properties
  - ✓ Ensure Pipeline Risks remain ALARP under the new service
  - ✓ Identify necessary practical & economic intervention actions to address unreasonable risks
  - ✓ Define MAOP
  - ✓ Confirm adequacy of ratings of ancillary pressure-rated pipeline components e.g. valves, flanges

Repurposing Natural Gas Pipelines

BUT… We need to tackle “new” mechanisms

- ✓ H_2 Embrittlement

Property	Effect of H_2
Strength	↔ (?)
Ductility	↓
Fracture toughness	↓

- ✓ H_2 Fatigue (↑)
- ✓ H_2 – Environmentally – Assisted Cracking (HEAC)

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Repurposing Natural Gas Pipelines

Impact of hydrogen vs materials

HE Mechanisms usually quoted

- Stress Induced Hydride formation and cleavage

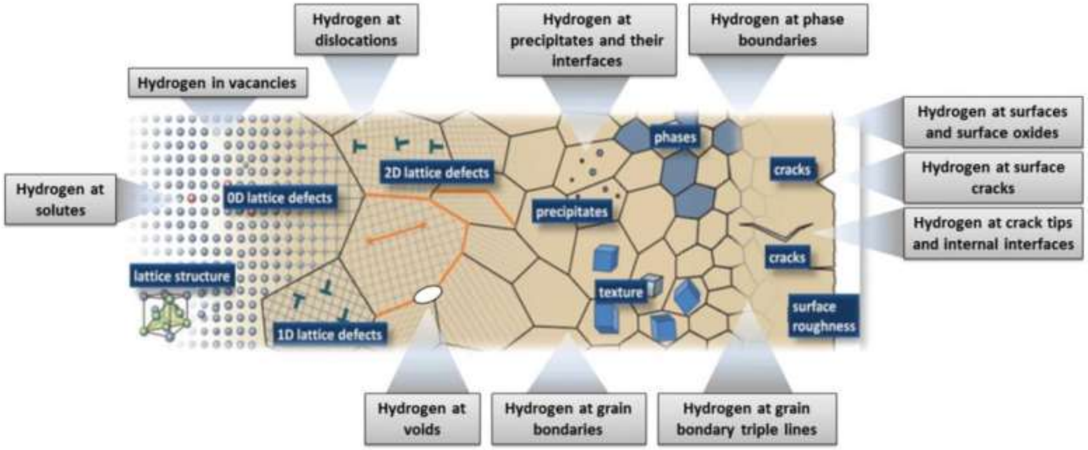
…. Metals with stable hydrides (Group Vb metals, Ti, Mg, Zr and alloys)

- Hydrogen-Induced Decohesion (HEDE)
- Hydrogen-Enhanced localised Plasticity (HELP)
- Adsorption-Induced Dislocation Emission (AIDE)

Dependent on
Microstructure, yield strength, number and structure of slip systems, specific material/environment system

Likely to be driven by a synergistic combination of aspects of the different theories

… Strong Personal views…



Repurposing Natural Gas Pipelines

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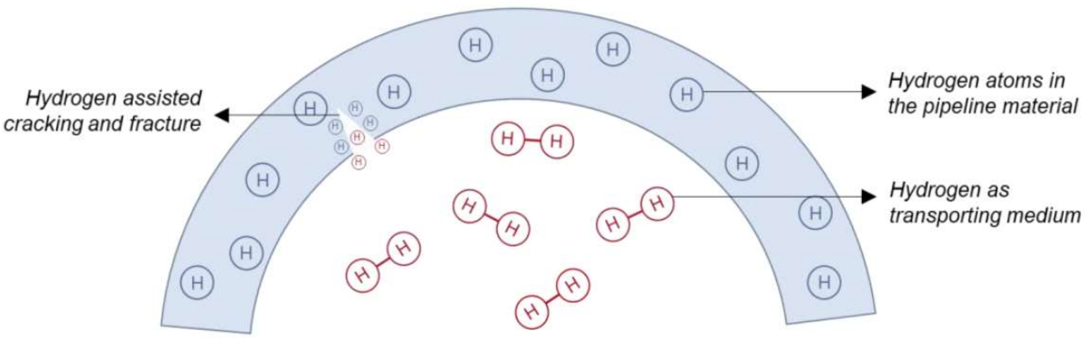
Impact of hydrogen vs materials



HEAC

Cracking believed to solely take place in the presence of pre-existing flaws or cracks (outside fatigue)

Cracking in bulk material away from cracks? (stress raisers, hard spots, etc.)

Existing codes & restrictions on higher grades

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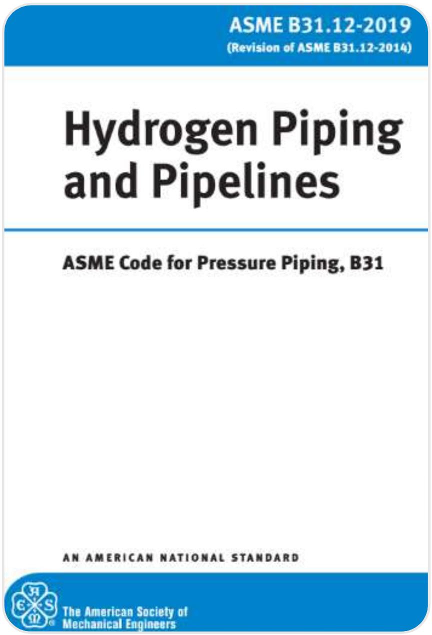
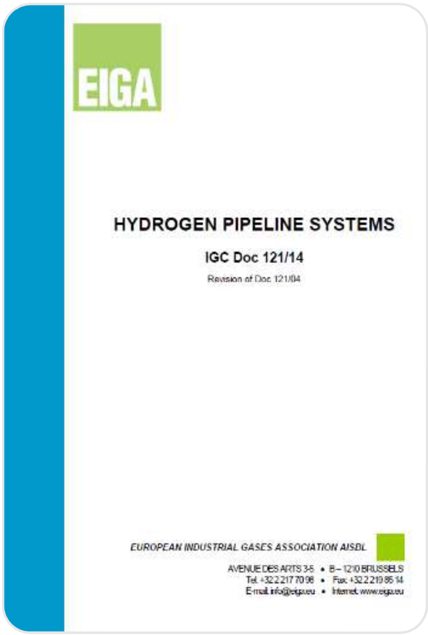

ASME B31.12-2019
(Revision of ASME B31.12-2014)

Hydrogen Piping and Pipelines

ASME Code for Pressure Piping, B31

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers


EIGA

HYDROGEN PIPELINE SYSTEMS

IGC Doc 121/14

Revision of Doc 121/04

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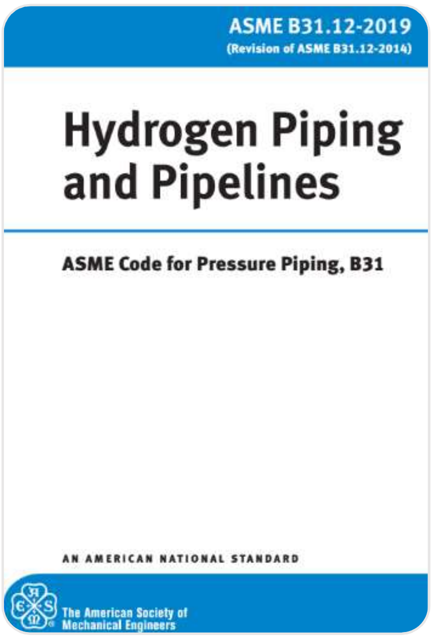
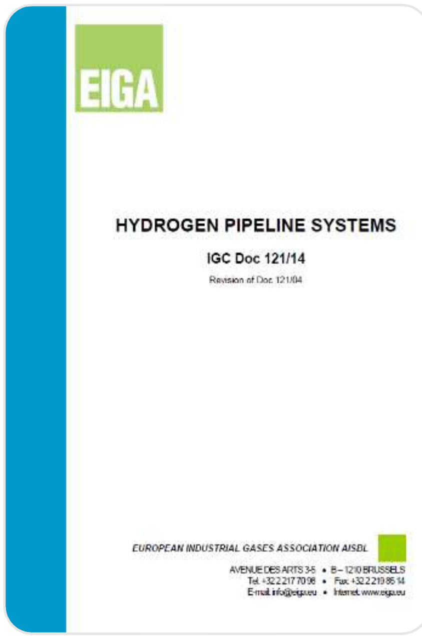
Existing codes & restrictions on higher grades





Preference for lower grades

EIGA / AIGA / CGA Guidelines:

"*it is recommended that only lower strength API 5L grades (X52 or lower) be used*"

ASME B31.12 Option A:

Materials Performance Factor penalises >X52

IGEM TD/1 Supplement 2:

Penalises >X52

EIGA / AIGA / CGA Guidelines:

"*This good service* [of ≤ X52] *is attributed to the relatively low strength of these alloys, which imparts resistance to hydrogen embrittlement and the other brittle fracture mechanisms*"

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Existing codes & restrictions on higher grades

Preference for lower grades

Option A (prescriptive / No H_2 testing)

Design Pressure

(NG) $P = \frac{2.S.t}{D}.F.E.T$ **Vs.** **(H_2)** $P = \frac{2.S.t}{D}.F.E.T.H_f$

Materials performance factor in H_2

Design Factor

Class location	NG	H_2
1	0.72	0.5
2	0.60	0.5
3	0.50	0.5
4	0.40	0.4

Table IX-5A Carbon Steel Pipeline Materials Performance Factor, H_f

Specified Min. Strength, ksi		System Design Pressure, psig				
Tensile	Yield	≤1,000	2,000	2,200	2,400	2,600
66 and under	≤52	1.0	1.0	0.954	0.910	0.880
Over 66 through 75	≤60	0.874	0.874	0.834	0.796	0.770
Over 75 through 82	≤70	0.776	0.776	0.742	0.706	0.684
Over 82 through 90	≤80	0.694	0.694	0.662	0.632	0.610

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Existing codes & restrictions on higher grades

Preference for lower grades

Design Pressure NG vs H_2…

32" diameter, 13.4 mm wall thickness, grade X70 / L485 pipeline

ASME Location Class	P_{H2} / bar per ASME B31.12 – Option A	P_{H2} / bar per IGEM/TD/1 Supplement 2*	P_{NG} / bar per ASME B31.8	Reduction in Pressure for H2 (B31.12 / TD/1) Compared to NG / %
1 Div 2	61	59	114	**47 / 48**
2	61	59	95	**36 / 38**
3	61	59	79	**23 / 25**
4	49	47	63	**23 / 25**

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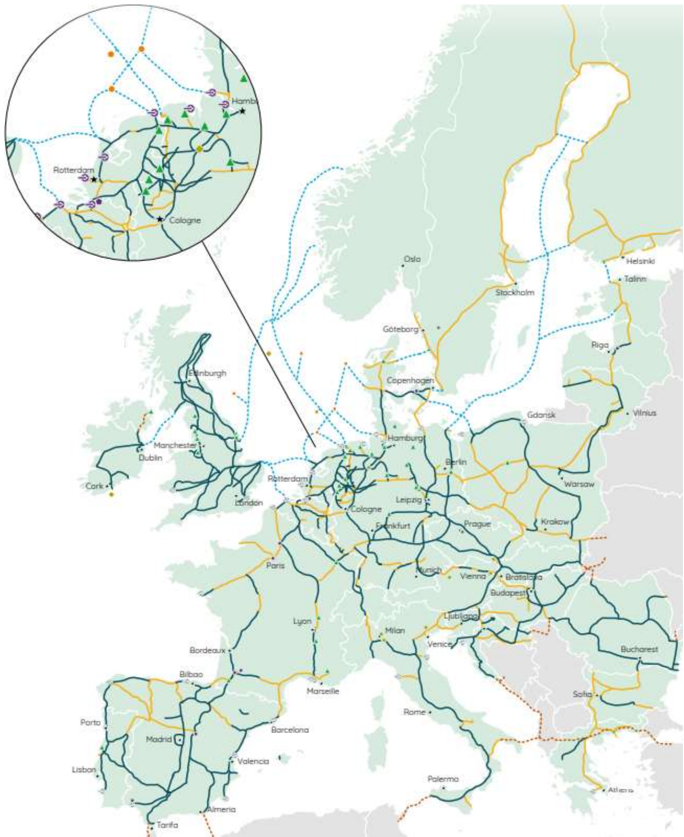
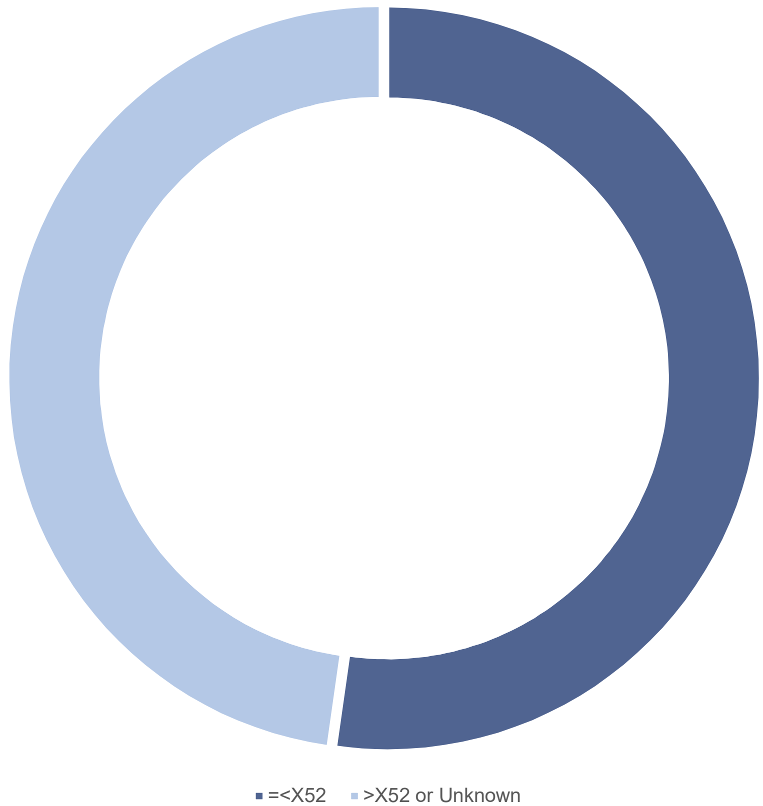
Prescriptive codes vs. Hydrogen Chain Value Challenges





53, 000 km EU H_2 backbone by 2040

~60% of the proposed hydrogen backbone will be repurposed existing pipelines

~48% of the existing infrastructure is >X52

Grades – an adequate metric for materials performance in H_2 ?

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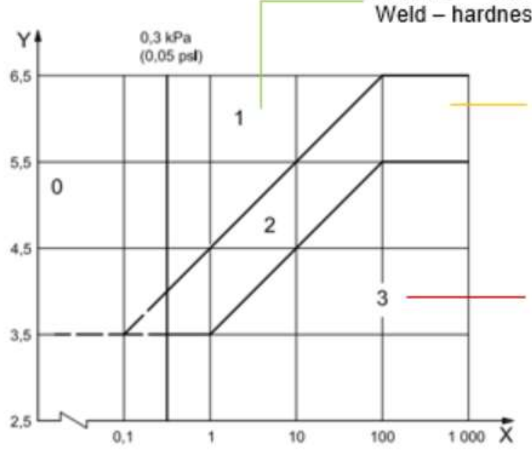
Grades – an adequate metric for materials performance in H2 ?

Use of high grades in hydrogen charging services?



Sour service Application

ISO 15156 / MR 0175

- HE generally controlled by hardness restrictions (<248 HV) for most severe applications
- But grades up to X65 approved by standard
- Use of high strength grades up to X80 also acceptable in milder H_2S

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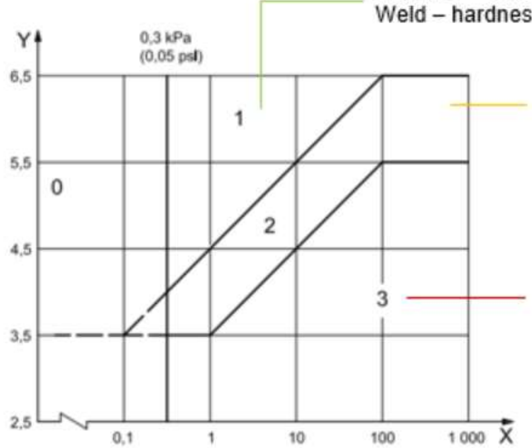
Grades – an adequate metric for materials performance in H2 ?

Use of high grades in hydrogen charging services?



Sour service Application

Caution

Pipeline grades not equal (vs. age)

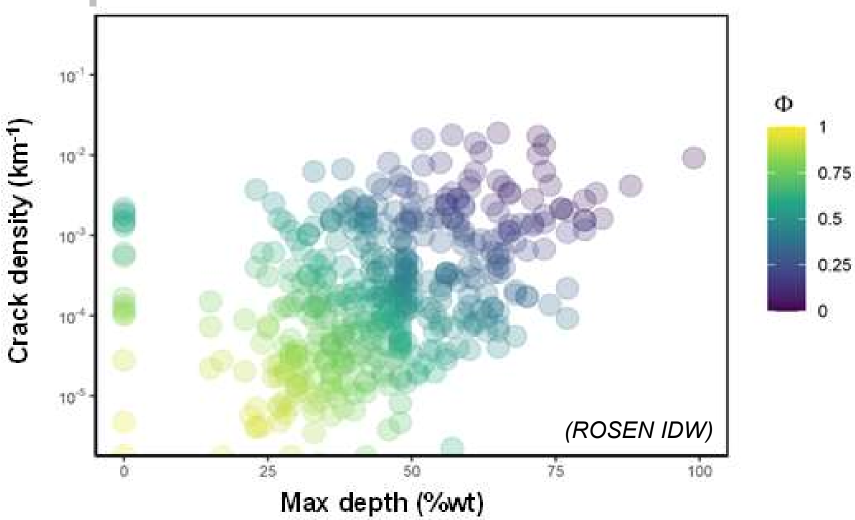
Validity of the sour standard requirements shall be cautioned against its year of revision and the quality of manufacturing and construction applicable at the time

Example illustrates the conservatism that may exist around unduly punishing the use of grades above X52

Grades – an adequate metric for materials performance in H_2 ?

Pipeline FFS in H_2 – Other key materials properties & correlation with grades?

Global gas pipeline condition vs cracking



- Pipeline Fitness vs crack
- Cracks acceptable in H_2?
- Key property- fracture toughness
- Fracture toughness vs grades?

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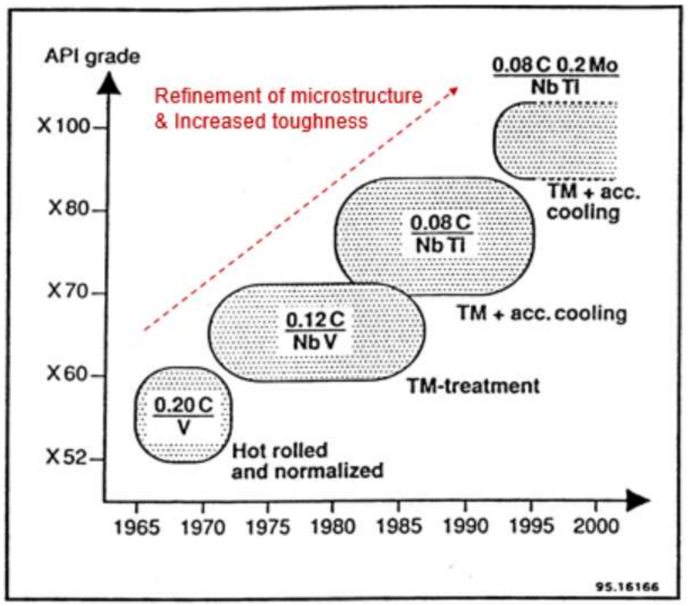
Grades – an adequate metric for materials performance in H_2 ?

Pipeline FFS in H_2 – Other key materials properties & correlation with grades?

Fracture toughness vs grades?



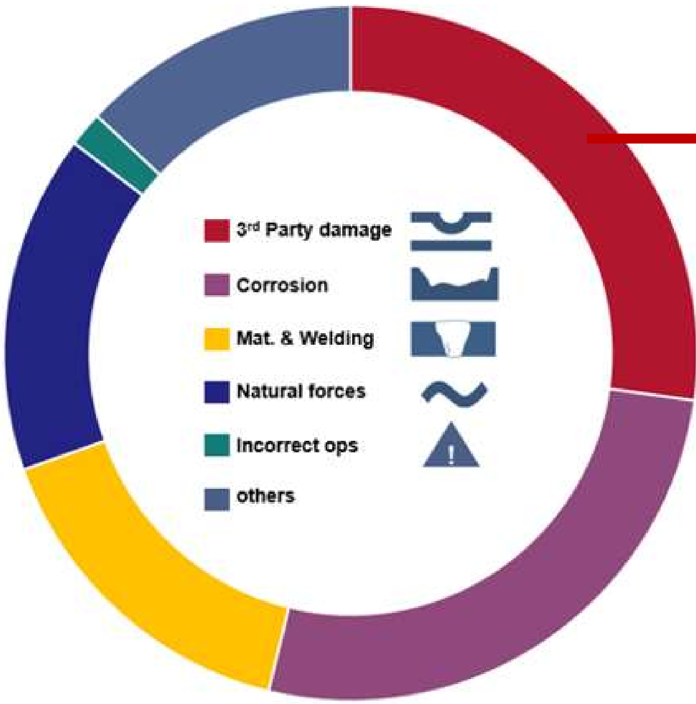
Properties as tested for a low strength (<X52) and a high Strength (X70) steel

Grade	YS (ksi)	UTS (ksi)	Y/T	Uniform Elongation (%)	Location	Test Temperature	Individual Impact Energy (J)	Shear Area (%)
X42 / L290	53	72	0.74	35	Pipe body	0°C	19, 16, 18	80, 70, 70
X70 / L485	72	96	0.75	34	Pipe body	0°C	308, 258, 275	100, 100, 100

►*If anything, higher grade = higher specified toughness*

Grades – an adequate metric for materials performance in H_2 ?

Pipeline FFS in H_2 – Other key materials properties & correlation with grades?



Pipeline Fitness vs 3rd party damage

Key property- Ductility

Proxy - Elongation

General expectation that increasing strength leads to decreasing ductility

API 5L Spec. minimum requirements for elongation 22% for Grade B & X42, to 15% for X80)

Too Conservative?

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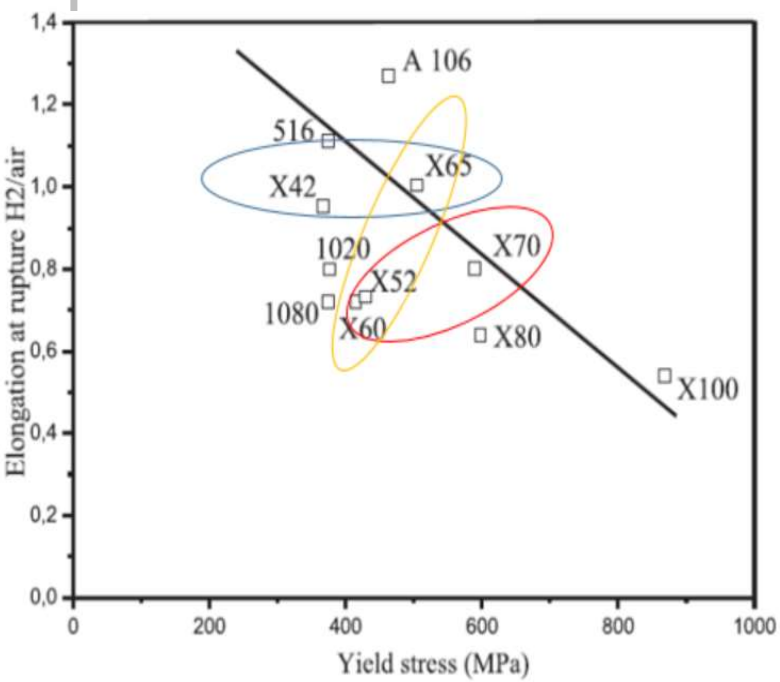
Grades – an adequate metric for materials performance in H_2 ?

Pipeline FFS in H_2 – Other key materials properties & correlation with grades?

Elongation vs grades?

Total Elongation ratio of various grades in hydrogen vs. air



► ***Higher grades ≠ bad suitability in all cases (vs low grades)***

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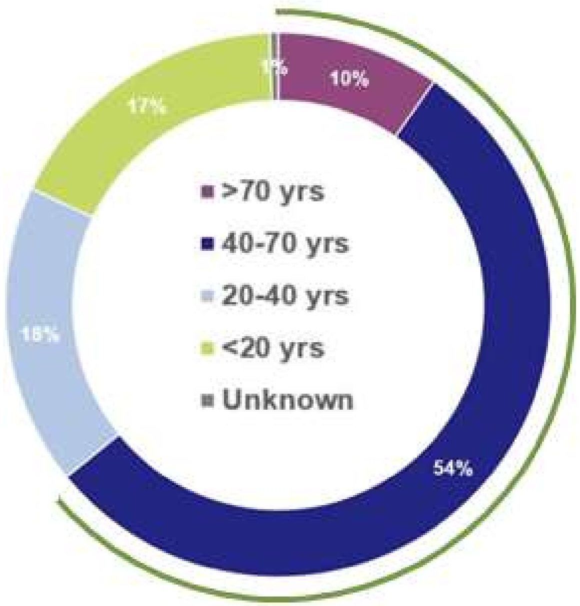
Grades – an adequate metric for materials performance in H_2 ?

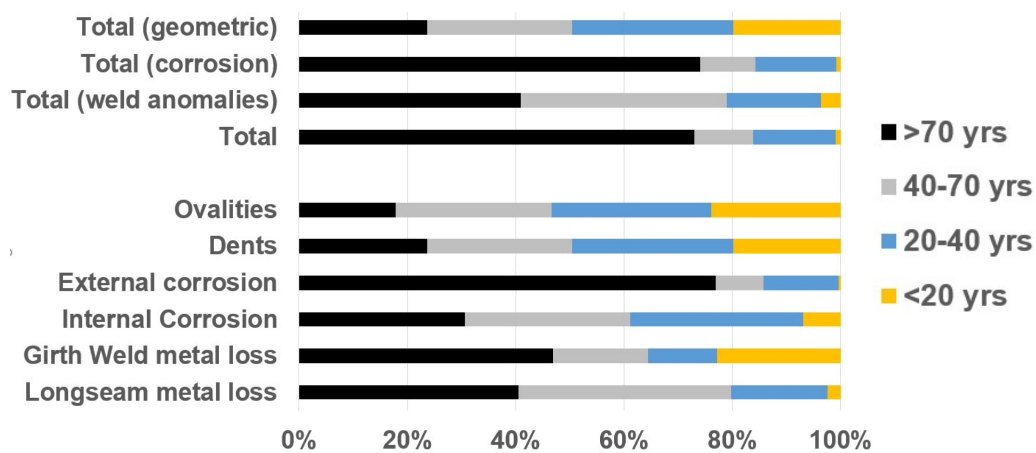
Pipeline FFS in H_2 – Other key materials properties & correlation with grades?

Integrity threats vs. age



65% >40 yrs

Pipeline condition vs integrity threats, worsens with age



►Existing low grade pipelines come with a higher integrity threat

Sandana D et al., Safe repurposing of vintage pipelines in North America, IPC 2022

Grades – an adequate metric for materials performance in H_2 ?

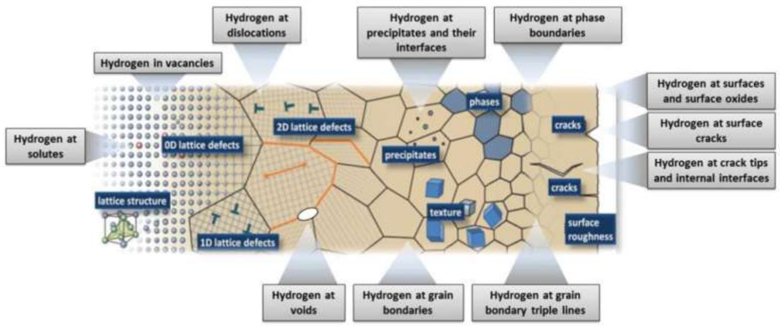
Importance of microstructure

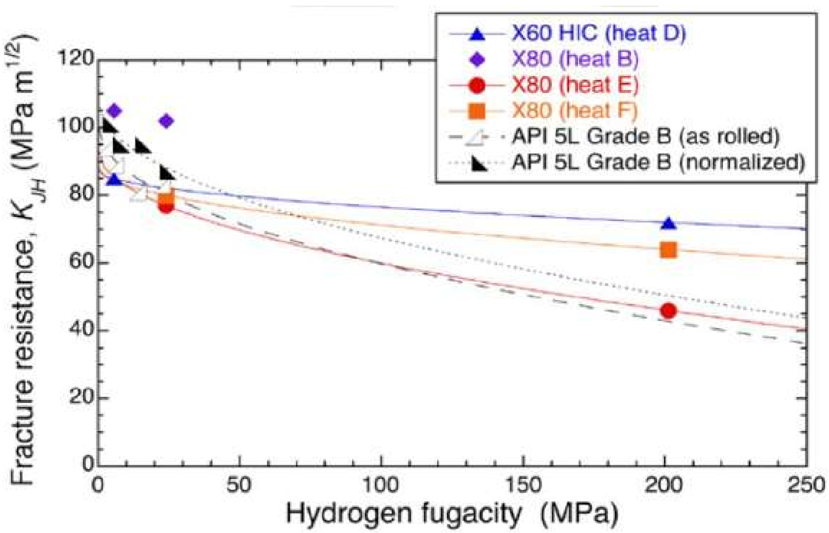
- **HE is a multivariate and complex problem**, from which variables associated with the microstructural (e.g. phases, chemistry) and macroscopic (e.g. grade, mechanical properties, stresses) level cannot be independently extracted and assessed in isolation.

- **Line pipe materials of a same nominal grade are not all equal against HE susceptibility and hydrogen service**

  - Overlaps between different domain of microstructures and pipe grades.

  - A grade can be achieved by different process routes and therefore microstructures.





Grades – an adequate metric for materials performance in H_2 ?

Predicting performance = f (grade, microstructure, chemistry)?

- 2 steels with very similar chemistry
- And Identical Nominal Grade (X52M)

Material	Element Concentration (wt.%)								
	C	Mn	Si	P	S	Al	Nb	V	Ti
MTR 1	0.04	1.06	0.20	0.01	0.001	0.03	0.03	-	0.01
MTR 2	0.04	1.07	0.21	0.01	0.002	0.034	0.032	-	0.014

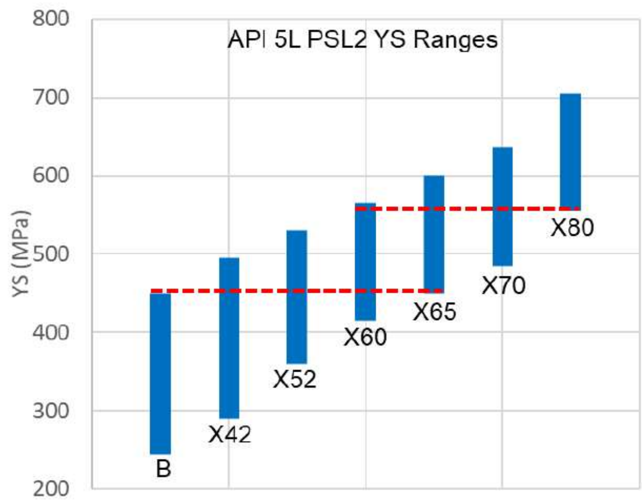
- **But very different mechanical properties**

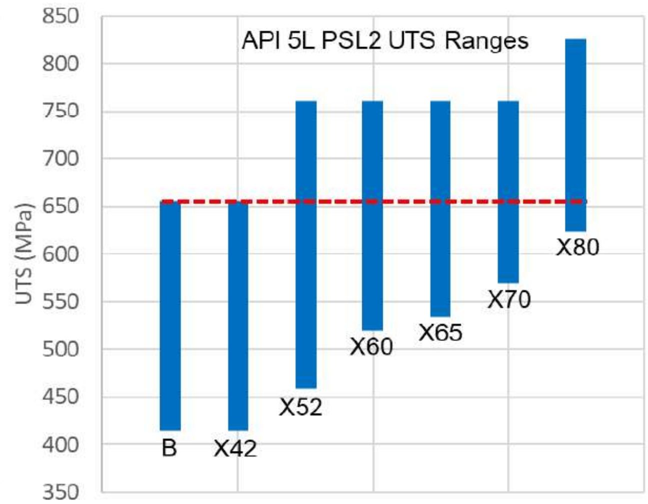
Material	Grade	YS (ksi)	UTS (ksi)	Y/T
MTR 1	X52M	78.7	81.2	0.97
MTR 2	X52M	61.1	72.4	0.84

Grades – an adequate metric for materials performance in H_2 ?

“Nominal” pipe grade vs. actual strength

- Pipe grade as a proxy to strength in order to discriminate the performance of line pipe materials in H_2
- Current guidelines favor the use of low strength grades up to X52
- **But grade is not even a good predictor of actual pipe strength**





Repurposing strategies – if not Grades – then what?

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Repurposing strategies – If not grades, then what?

1. Predicting performance = f (grade, microstructure, chemistry)? Challenging

2. Assume specified minima Charpy energies, convert to "true" fracture toughness and apply a "knockdown" factor to account for hydrogen

   - Charpy data may not exist for many pipelines (pre-2000 and PSL 1)

3. Assume hydrogen is the "great leveller" and that hydrogen affected fracture toughness for all steels converges around the same level (~50 $ksi.in^{1/2}$ / 55 $MPa.m^{1/2}$)

   - Limited empirical data supporting this, no compelling mechanistic justification available, may be over- or non-conservative

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Repurposing strategies – If not grades, then what?

Materials 'performance' behaviour under H_2?

- Guidelines … undue conservatism?
- Is a steel <= X52 automatically suitable?
  (hard spots, heavy banding, etc.)
- Is a steel > X52 inevitably unsuitable?
  (X65 / X70… Sour service)

Severity of hydrogen issues (e.g. reduction in toughness, crack susceptibility) largely modulated by steel microstructures and chemistries rather than just grade

→ **Testing of representative linepipe materials**

ASME B31.12 - Option B

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Repurposing strategies – If not grades, then what?

Materials ‘performance’ behaviour under H_2?

- **Emphasis**

  understanding of the actual pipeline material (s) population and DNA, and the testing of representative linepipe materials ‘performance’ behaviour under H_2

► **Where do we need to SAMPLE?**
(TVC materials certificates – incomplete or missing)

- **ASME B32.12, PL-3.21**

  Conduct material sampling every 1 mile (1.6 km)

► **Cost effectiveness? Practicality?**

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Repurposing strategies – If not grades, then what?

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Materials ‘performance’ behaviour under H_2?

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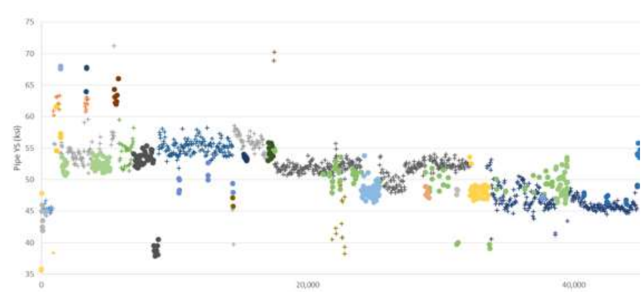
  Conduct material sampling every 1 mile (1.6 km)

► **Cost effectiveness? Practicality?**

- **ROSEN Approach**

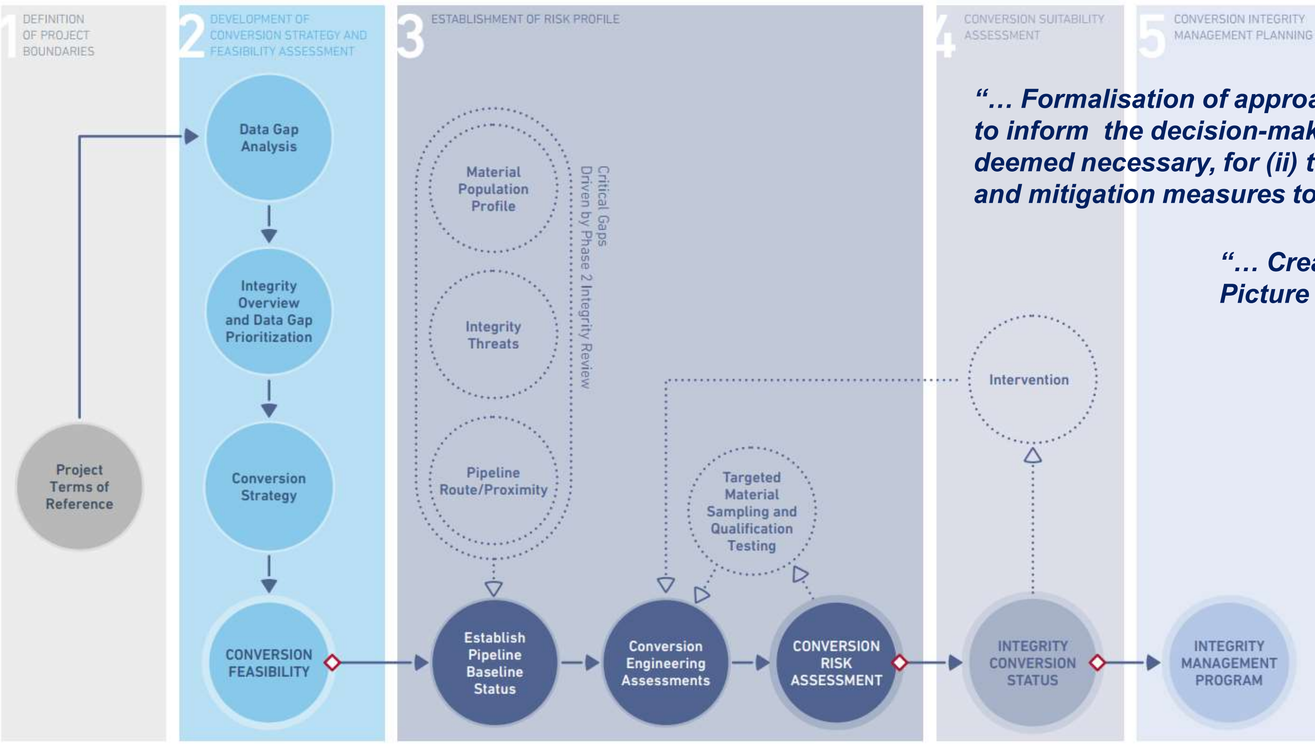
  Material population & Risk- driven approach

► development of **TARGETED** linepipe sampling strategies by **integrating the knowledge** of materials populations, threat susceptibility profiles, baseline condition and consequences.



Material population profiles
(Certificates, ROMAT-pgs)
+
Baseline condition ass.
+
Threat susceptibility profiles
+
Risk profiles

Conclusions – ROSEN Hydrogen Integrity Roadmap



"… Formalisation of approach to collect the necessary engineering inputs in order to inform the decision-making process for (i) the suitability to repurposing, or if deemed necessary, for (ii) the development of practical economic rehabilitation and mitigation measures to achieve safe conversion…"

"… Creating a representative and accurate Picture of pipeline risk profile for safe repurposing…"

- Sampling & Materials performance testing at core of Strategy
- Sampling = Understand your Materials DNA & profile
- Decision led by Pipeline Integrity & Risk

- *Sandana D et al., Safe repurposing of vintage pipelines in North America, IPC 2022*
- *Ruiz Martinez et al. A practical guide to repurpose existing pipelines for transporting H2, OMC 2023*

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