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EPRG

EPRG Hydrogen Pipelines Integrity Management and Repurposing Guideline White Paper

Rev.1

EPRG Hydrogen Pipelines Integrity Management and Repurposing Guideline White Paper

Executive Summary

EPRG has launched a significant H_2 pipeline research programme with the ultimate aim of developing a Guideline for repurposing existing onshore/offshore pipelines to H_2 service and a Guideline for new onshore/offshore H_2 pipelines.

There are many existing industry design codes which reference hydrogen, the most detailed being ASME B31.12-2019 [1] with other standards taking this code as a basis. B31.12 is challenging to apply practically to repurposing pipelines, particularly accounting for historic defects and damage and does not incorporate the latest research knowledge with specific application to Europe.

In the interim, due to the industry and government requirements to repurpose existing pipelines to H_2 service at an accelerated pace, the rapid evolving research developments in this area, and conscious that standards development cannot keep pace, EPRG has decided to develop a repurposing Guideline white paper that:

- Provides practical interim guidance on several requirements and input parameters (identified as key aspects in this Guideline) in ASME B31.12 Option A and B using a three-level approach depending primarily on the operating envelope and existing condition of the pipeline. The general philosophy behind these three levels is shown below, and further details may be found in the relevant appendices:
  - Level 1: Screening assessment for low pressure pipelines aligned to B31.12 Option A
  - Level 2: Standard assessment for higher pressure pipelines aligned to B31.12 Option B but with minimal fatigue pressure/longitudinal loading in line with the recently issued DVGW G464 [2] or higher-pressure pipelines assessed according to experimentally derived S-N curves
  - Level 3: Detailed assessment for higher-pressure pipelines aligned to B31.12 Option B with possibly higher fatigue pressure/longitudinal loading and/or potentially defects outside B31.12 limits and/or higher static loading in the longitudinal direction.
- Guidance for these key aspects is given with background commentary and identification of gaps either to be closed or requiring a new research programme.
- Identification of gaps that are being closed by ongoing research and gaps that are outstanding.

This Guideline is intended to augment existing standards with non-mandatory clarification guidance. Where aspects/requirements are not covered, it is deemed that B31.12 is clear and requires no further clarification. This Guideline should not be used as a design code. In some instances, the requirements in B31.12 may have been superseded by recent advances in research since the last publication in 2019, and in these cases, it is recommended that the specific requirement be discussed with the jurisdictional authorities to determine if this can be revisited, recognising that the jurisdictional authorities are the ultimate authority in these matters.

The Guideline is aimed at repurposing pipelines for near pure (effectively 100%) H_2 service and can be applied for any intentional addition of hydrogen (conservative for blends). The principles outlined in this Guideline could be used for new H_2 pipelines, however a guideline for new pipelines would also have to consider, amongst other things, pipe quality and construction specifications.

It is recommended that standards bodies consider an additional appendix to cover hydrogen service, including blends <10%, and that consideration be given to this guideline and future iterations thereof. **Although this document is structured to match the clauses and requirements of B31.12-2019, it is the view of EPRG that the technical details and recommendations covered in the following sections remains applicable for new standards and should be considered for inclusion even if captured in an alternative layout**, such as a hydrogen appendix to an existing standard instead of a standalone document such as B31.12 is now.

It has been assumed in the preparation of this Guideline that the execution of its provisions will be entrusted to appropriately qualified and experienced people, for whose use it has been produced.

This interim white paper guidance will be updated once more gaps are closed to more definitive guidance with the aim to present to standards bodies for their consideration.

Rev.	Date	Description	Prepared by	Reviewed by
0	01/02/2023	Initial Issue – for EPRG review	Neil Gallon, Sarah Hopkin, and Tom Martin	EPRG H2 Taskforce
1	12/06/2023	Revised following EPRG comments	Neil Gallon, Sarah Hopkin, and Tom Martin	

Contents

Introduction

There are existing industry design codes which reference hydrogen, the most detailed being ASME B31.12 [1]. The most recent edition of B31.12 was issued in 2019 and many other standards take this code as a basis. There is an industry and government focus to repurpose existing pipelines to H_2 service at an accelerated pace. This means the focus on hydrogen pipelines is rapidly increasing, with significant cross-industry research ongoing on a variety of different topics. As a result of this speed, design codes are struggling to keep up with advances in ongoing research. B31.12 is challenging to apply practically to repurposing pipelines, particularly accounting for historic defects and damage, and does not provide detailed guidance on managing integrity once in hydrogen service. The timelines to improve such standards do not match the industry requirements for guidance.
EPRG has launched a significant H_2 pipeline research programme with the ultimate aim of developing a Guideline for repurposing existing onshore/offshore pipelines to H_2 service and a Guideline for new onshore/offshore H_2 pipelines. Combined with the rapidly evolving research developments in this area, this means standards development cannot keep pace. Therefore, as part of these efforts, EPRG is publishing this repurposing Guideline white paper that:

- Provides practical interim guidance on several requirements and input parameters (identified as key aspects in this Guideline) in B31.12 Option A and B using a three-level approach depending primarily on the operating envelope and existing condition of the pipeline as follows:
    - Level 1: Screening assessment for low pressure pipelines aligned to B31.12 Option A
    - Level 2: Standard assessment for higher pressure pipelines aligned to B31.12 Option B but minimal fatigue pressure/longitudinal loading in line with the recently issued DVGW G464 [2] or higher-pressure pipelines assessed according to experimentally derived S-N curves
    - Level 3: Detailed assessment for higher pressure-pipelines aligned to B31.12 Option B with possibly higher fatigue pressure/longitudinal loading and/or potentially defects outside B31.12 limits and/or higher static loading in the longitudinal direction.
- Guidance for these key aspects is given with background commentary and can be broadly delineated into three categories:
    - Established Guidance: Research has been concluded leading to definitive guidance.
    - Provisional Guidance: Research is ongoing, but results are favourable to allow provisional guidance to be made. The research projects are identified, and these are labelled as an ongoing gap.
    - Lack of Advice: No research is currently identified to close the outstanding gap.
    - Identifies gaps that are being closed by ongoing research and gaps that are outstanding with the intention as more gaps are closed by ongoing or new research this interim white paper guidance will be updated to more definitive guidance with the aim to present to standards bodies for their consideration.

In developing the interim guidance, ASME B31.12-2019 is used as a base. Through workshops and meetings, EPRG has identified key aspects that should be covered in this Guideline, which also builds on existing EPRG H_2 Pipelines publications, most notably the Literature Review (EPRG 221/2020) [3] and Integrity Assessment Methods (EPRG 221/2021) [4]. European standard EN 1594 [5] for onshore gas pipelines for pressures greater than 16 bar has a draft version for hydrogen service that refers mainly to B31.12. DNV-ST-F101 [6], aimed at offshore pipelines, does not address hydrogen service specifically but guidelines are presently being developed as part of a joint industry project [DNV JIP H2Pipe]. It is recommended that standards bodies consider an additional appendix to cover hydrogen service and that consideration be given to this guideline and future iterations thereof. **Although this document is structured to match the clauses and requirements of B31.12, it is the view of EPRG that the technical details and recommendations covered in the following sections remains applicable for**

new standards, and should be considered for inclusion even if captured in an alternative layout, such as a hydrogen appendix to an existing standard instead of a standalone document such as B31.12 is now. This interim white paper guidance will be updated once more gaps are closed to more definitive guidance with the aim to present to standards bodies for their consideration.

The Guideline is aimed at repurposing pipelines for near pure (effectively 100%) H_2 service and can be applied for any intentional addition of hydrogen (conservative for blends). The principles outlined in this Guideline could be used for new H_2 pipelines, however a guideline for new pipelines would also have to consider, amongst other things, pipe quality and construction specifications.

The following sections of this Guideline outline the approach used in its development. The main body of the document identifies the philosophy and reference guidelines for each level, the ongoing gaps being investigated and outstanding gaps. The actual guidance notes, including commentary and gaps for key aspects of each level are in accompanying appendices.

Definitions

- K_{max} – the onset of da/dt established from Paris Law as ΔK approaches zero.
- $K_{1H\text{-}E1681}$ – obtained from constant load/displacement threshold stress intensity factor fracture toughness test as outlined in ASTM E1681 [7].
- $K_{1H\text{-}E1820}$ – obtained from the rising load fracture toughness test outlined in ASTM E1820 [8] (or equivalent), indicating the point of catastrophic failure
- DK_{th} – the onset of fatigue crack growth defined by a certain minimal da/dN, e.g., 10^{-6} mm/cycle.
- Vintage/modern steel - Throughout this document, the terms "vintage" and "modern" are used to give some guidance and very high-level categorisation of parent material and welds. It is emphasised that these terms are not formally defined, and as such care should be taken when they are being used. Grouping of materials into "vintage" or "modern" is not a substitute for a detailed analysis of the microstructure and properties of the pipe. The use of "vintage" within this document is intended to mean older pipes which are likely to have a ferritic / pearlitic microstructure, grain structure can be coarser, and the level of impurities and inclusions can be high. As a result of this, "vintage" pipes tend to have poorer mechanical properties (in particular in-air toughness) than their "modern" equivalents. "Vintage" pipes may also have larger manufacturing flaws than their "modern" equivalents due to advances in steel processing and NDT over the years. In particular "vintage" welds can be of more variable, and often poorer quality than their "modern" equivalents. "Vintage" girth welds will generally have been subject to a less rigorous QC regime, and a lesser degree, if any, of NDT inspection leading to them potentially having both poorer properties and more defects than their "modern" equivalent. While this means that "vintage" and "modern" are easy labels to apply, it needs to be emphasised that they should not be used as a formal classification. Age in itself can be part of a grouping system when assessing existing pipes for suitability for hydrogen conversion, but it needs to be considered along with other factors which may have an effect, including the manufacturing process (coil or plate feedstock, seamless), welding process (longitudinal or spiral SAW, low or high frequency electric welding etc.), supply condition (thermomechanical-rolled feedstock or thermomechanical formed pipe (HFW only), quench and tempered, etc.) and others. As identified elsewhere in this document (Gap 1.10 and 1.12) the development of common material groupings is considered a gap still to be addressed.

Approach

The EPRG Hydrogen Pipelines Repurposing, and Integrity Management Guideline takes as its basis Option A and B of section PL3.7 of ASME B31.12-2019. The Guideline has three levels. The overview of each level is summarised in the following sections, with individual recommendations covered in the respective appendices as follows:

- Level 1:
  - Screening assessment not requiring the user to have a detailed fracture mechanics background.
  - Aimed at low pressure pipelines with low axial stresses, aligned to B31.12 Option A
  - Detailed guidance is given in Appendix 1.
- Level 2:
  - Standard assessment requiring the user to have a fracture mechanics background.
  - Level 2A – Aimed at higher-pressure pipelines aligned to B31.12 Option B but minimal fatigue pressure and longitudinal fatigue loading in line with the recently published DVGW G464. Detailed guidance is given in Appendix 2.
  - Level 2B – Aimed at higher pressure pipelines assessed according to experimentally derived hydrogen S-N curves. Detailed guidance in Appendix 3.
- Level 3:
  - Detailed assessment requiring the user to have a detailed fracture mechanics background.
  - Higher pressure pipelines aligned to B31.12 Option B with possibly higher fatigue or static loading and/or potentially defects outside B31.12 limits.
  - Detailed guidance is given in Appendix 4.

Each Level is further divided into guidance related to the following three categories with several aspects for each category:

Degradation and defects	
	Degradation
	Planar Defects
	Body Planar Defects
	Volumetric Defects
	Dents/Combinations
	Wrinkling/buckling/local deformation/large strain events
	Others
Loading and Operations in H2 service	
	Loading
	Design factors and derating factors, including location classes (onshore) and freespan / longitudinal stresses and cyclic loading (offshore)
	Loading limitation due to static crack growth (da/dt)
	Failure modes/limit states linked to environment e.g. onshore versus offshore etc.
	Operations e.g. pressure monitoring
	Integrity Management
	Gas Composition - Hydrogen limits and the use of inhibitor molecules
	Corrosion protection (internal and external coatings, clad layers, CP)
	Inspection (Preparation for H2 service and inspections once H2 service has commenced)
	Repairs

Material Requirements & Restrictions	
	Hardness
	Air Toughness (CVN)
	H2 Fracture Toughness
	Ductility
	Fatigue
	Material Testing
	Grade
	Yield Strength
	UTS
	Microstructure and chemical composition
	Fracture arrest (running brittle fracture) - DWTT
	Fracture arrest (running ductile fracture) - CVN
	Residual stresses

For each aspect, e.g. planar defects, the following is itemised:

- Guidance is given and may be either established guidance, provisional guidance, or no advice if a gap exists.
- Commentary outlining the logic and rationalisation behind the guidance.
- Gaps are itemised and are assigned colour coding as follows:
  - Orange (O): the gap is the subject of ongoing research
  - Red (R): the gap is an outstanding gap with no active research to close it
  - Blue (B): the gap is covered under a different aspect in this Guideline

At higher levels there may be no guidance in addition to that available for lower levels. In such cases the Guideline appendices reference the lower-level guidance that should be used.

This Guideline is intended to augment existing standards with non-mandatory recommendations. Where aspects/requirements are not covered, it is deemed that B31.12 is clear and requires no further clarification. This Guideline should not be used as a standalone design code. In some instances, the requirements in B31.12 may have been superseded by recent advances in research since the last publication of B31.12, and in these cases, it is recommended that the specific requirement be discussed with the jurisdictional authorities to determine if this can be revisited, recognising that the jurisdictional authorities are the ultimate authority in these matters.

The Guideline is aimed at repurposing pipelines for near pure (effectively 100%) H_2 service and can be applied for any intentional addition of hydrogen (conservative for blends). The principles outlined in this Guideline could be used for new H_2 pipelines, however a guideline for new pipelines would also have to consider, amongst other things, pipe quality and construction specifications.

It has been assumed in the preparation of this Guideline that the execution of its provisions will be entrusted to appropriately qualified and experienced people, for whose use it has been produced.

Level 1: Screening assessment

Level 1 Philosophy

Level 1 is based on ASME B31.12 Option A. It is tailored to enable a simple screening method. See Appendix 1 for full details. Level 1 provides additional recommendations to ensure pipeline integrity for situations not covered originally in B31.12 Option A, for example offshore applications, additional loads besides pressure loading (since B31.12 focuses on pressure loading concentrating on the seam weld), and different degradation mechanisms.

It revisits B31.12 Option A requirements that are not straightforward to apply that are not considered to have a suitable technical justification, subject to approval of relevant jurisdictional authority (such as Clause PL 3.21 (l): if material cannot be qualified to Option A or B, MAOP shall be selected to limit MAOP below or equal to 40% SMYS at all points along the pipeline).

Level 1 does not require a detailed fracture mechanics background but an appreciation of the influence of input parameters in a fracture mechanics analysis is recommended in conjunction with an appreciation of the influence of H_2 on material properties.

Level 1 Reference guidelines

Base Guideline/Standard:

- B31.12-2019 Option A [1]

Other Guidelines/Standards:

- EIGA / AIGA / CGA Guideline IGC Doc 121/14 [9]
- IGEM TD/1 H_2 Supplement [10]
- BS7910 [11]
- B31.G [12]
- CEN/TR 17797 [13]

Guidelines in preparation:

- EN 1594 - H_2 appendix out for comment
- API 1104 + API 5L - any future H_2 supplements
- DNV-ST-F101 - H_2 appendix - under development
- AS/NZS 2885-1 - H_2 amendments
- ISO 13623 - optional appendix for H_2
- CSA Z662 – Clause 17 on H_2 to be published in 2023

Level 2A & B: Standard assessment

Level 2A Philosophy

Level 2A is the standard assessment level based on ASME B31.12 Option B. See Appendix 2 for full details. Level 2A provides additional requirements to ensure pipeline integrity for situations not covered originally in B31.12 Option B, for example offshore applications, additional loads besides pressure loading (B31.12 is primarily aimed at onshore pipelines where hoop loading concentrating on the seam weld is of concern whereas for offshore loading other longitudinal loads, and hence the girth welds, may also need to be considered), and different degradation mechanisms. Level 2A covers pipelines that experience minimal fatigue longitudinal fatigue loading, in line with the recently DVGW G464.

Level 2A revisits B31.12 Option B requirements that are not considered manageable with a suitable technical justification subject to approval of relevant jurisdictional authority. See Appendix 2 for full details.

Level 2A is tailored to enable an assessment without conducting a fracture mechanics-based fatigue analysis by ensuring that ΔK is less than a fatigue threshold (ΔK_{th}). This level can only to be used when the material has been confirmed to exhibit a fatigue threshold and there is not time dependent da/dt crack growth present for the intended maximum K values. If the anticipated defect size is not significant (e.g., less than or equal to workmanship – see 'Degradation and Defects' section in Appendix 1) then this effectively means that there will be a limitation on ΔP, although the resulting impact of $\Delta K<\Delta K_{th}$ will have to be confirmed.
Material testing in H_2 (as a minimum fracture toughness, ductility, and threshold for the onset of da/dt) is required unless material test data of equivalent material (See Gaps 1.10, 1.11 and 1.12) and conditions is available.

Level 2A requires a fracture mechanics background with an appreciation of the influence of H_2 on material properties.

Level 2A Reference guidelines

Base Guideline/Standard:

- B31.12 Option B in conjunction with ECA standards

ECA standards:

- BS7910
- API 579-1 [14]
- (DNV RP F108 – select clauses only) [15]
- DVGW G464 [2]

Other Guidelines/Standards:

- As for Level 1
- PVP2022-84757 [16]

Guidelines in preparation:

- As for Level 1

Level 2B Philosophy

Level 2B is also the standard assessment Level based on ASME B31.12 Option B. See Appendix 3 for full details. However, it is based on the use of S-N curves. As for Level 2A, Level 2B provides additional requirements to ensure pipeline integrity for situations not covered originally in B31.12 Option B, for example offshore applications, additional loads besides pressure loading (B31.12 focuses on thin wall pressure loading concentrating on the seam weld), and different degradation mechanisms. It revisits B31.12 Option B requirements that are not considered manageable with a suitable technical justification subject to approval of the relevant jurisdictional authority.

This S-N approach is typically used in offshore applications but at present there is a lack of S-N data for hydrogen pipelines in the literature and the approach can be considered very much at the initial research phase. A specific EPRG project may be needed to establish standard S-N curves for hydrogen.

Considerations that will have to be addressed include the defect size that is selected as the basis of the S-N curve tests or what correction factor should be employed to account for defects. Furthermore, it is currently uncertain what the boundaries of the approach are, beyond which a more detailed Level 3-type assessment is recommended.

Level 2B requires a detailed fracture mechanics background with an appreciation of the influence of H_2 on material properties.

Level 2B Reference guidelines

In addition to the reference guidelines from Level 2A, it is premature at this stage to recommend a base standard. However, in future this will likely be the updated DNV-ST-F101 H2 appendix, combined with B31.12 Option B in conjunction with an ECA standard

ECA standards:

- As for Level 2A

Guidelines in preparation:

- DNV-ST-F101 - H_2 appendix - under development

Level 3: Detailed assessment

Level 3 Philosophy

Level 3 is the detailed assessment Level based on ASME B31.12 Option B. See Appendix 4 for full details. Level 3 provides additional requirements to ensure pipeline integrity for situations not covered originally in B31.12 Option B, for example offshore applications, additional loads besides pressure loading (B31.12 focuses on thin wall pressure loading concentrating on the seam weld), and different degradation mechanisms. Fatigue pressure and longitudinal fatigue loading limits will be higher than for level 2, and defects may fall outside the limits covered in B31.12. Level 3 revisits Option B requirements that are not considered manageable with a suitable technical justification subject to approval of the relevant jurisdictional authority.

Level 3 is tailored to enable assessment using an ECA approach according to Option B in conjunction with standard ECA codes and guidelines. It is aimed at the situation where the loading, defect size and/or environment etc. may result in ΔK greater than ΔK_{th} for fatigue.

Level 3 requires a fracture mechanics knowledge with understanding of the influence of H_2 on the material properties.

Level 3 Reference guidelines

Base Guideline/Standard:

- B31.12 Option B in conjunction with ECA standards

ECA standards:

- As for Level 2A

Other Guidelines/Standards:

- As for Level 2A

Guidelines in preparation:

- As for Level 2A

Gaps and Gap Closure Plan

Appendices 1-4 capture the remaining gaps, and the current gap closure plan in place, if available. Note that where projects are listed relevant to a specific gap, this does not guarantee that the gap will be closed completely by the named project. In summary, these gaps are:

Gaps being worked

For each gap there is a number, e.g. Gap x.y, where x is the level and y is the gap number. It should be noted that the following list of gaps are a high-level overview with a lot more detail included for each of the gaps in the appendices along with supporting commentary.

Degradation and defects

- *Gap 1.1 Planar defects (O):* Recommended defect size and the impact of hydrogen on internal flaws. B31.12 does not cover gap explicitly.
  There is an EPRG Project 231 and 232 in progress to justify the proposed defect size guidelines.
- *Gap 1.3 Volumetric defects (O):* There is a gap to show whether ductility is influenced by H_2 below UTS, and hence plastic collapse. The volumetric flaw assessment procedures as per ASME B31.G or DNV RPF-101 are based on UTS and yield strength.
  Gap is open and can be closed by numerical/experimental programme (SafeH2Pipe).
- *Gap 1.4 Dents and combinations of mechanical damage (O):* There is a gap on the acceptability of dents or dent/gouge combinations beyond current B31.12 limits.
  Gap is open and can be closed by numerical/experimental programme (SafeH2Pipe).

Material requirements and restrictions

- *Gap 1.7 Hardness (O):* The current recommendation is to relax the limits from B31.12 to 275HV10 (average), with a maximum hardness of 300HV10. This recommendation is based on limited data and should be confirmed with jurisdictional authorities. There is still an open gap on understanding the impact of higher levels of hardness on material properties in H_2. A plan is in place and being executed: EPRG Projects 231 and 232 are looking at hardness effect on fatigue crack growth and fracture toughness (normal and high hardness girth welds) and difference in microstructure. In addition, there are multiple other projects which are testing a wide range of different materials, including two DNV JIPs and a programme initiated by the H_2 Fuel Task Group in API 1104 (see also Gap 1.12).
- *Gap 1.9 Air toughness (CVN (O)):* How to manage vintage welds with low toughness in air. Initial research suggests performance is similar to modern materials with higher toughness, but there is a gap closure plan that is presently being executed. The following research programmes are addressing this issue: SyWestH2, DNV integrity JIP, and HyBlend.
- *Gap 1.10 Material testing (O):* There is a gap on developing common groupings based on for example microstructure, grade, vintage, manufacturing method etc.
  This gap is being worked, and numerous ongoing JIP's will provide input into developing common groupings. It is a high priority gap to resolve.
- *Gap 1.12 Microstructure and chemical composition (O):*
  There is a gap with respect to the recommendations of non-mandatory Appendix G of B31.12 and existing pipe materials, with respect to the requirements of Annex A of ISO 3183 [17] and

Annex H of API 5L [18]. To address this gap, and to assess whether $K_{IH-E1820}/K_{IH-E1681}$ ever falls significantly below 60 MPa√m, EPRG projects 231 and 232 are ongoing, together with numerous other projects (for example the DNV JIP H2Pipe and the DNV Integrity JIP and the SyWest H2 project). These projects are testing a wide range of existing pipes of different ages and manufacturing routes. General types of parent material microstructure will need to be assessed. A separate classification will be required for the seam and girth welds if these have average hardness over 275 HV10 and a maximum of 300HV10.

- *Gap 1.14 Fracture arrest (running ductile fracture) – CVN (O)*
  - Speed of running ductile fracture would probably be too quick for hydrogen to affect the resistance to running ductile fracture but this has not been proven and thus remains a gap
  - The decompression curve of hydrogen is less onerous than natural gas (including blends)

  Considering the above, although not proven, it is felt that the likelihood of running ductile fracture is low if API-5L Annex G is followed; it is still a gap but considered of low priority. This is also being investigated by the DNV H2Pipe JIP.
- *Gap 2.1 H_2 fracture toughness (O):* There is a gap to develop simplified recommendations on toughness performance in H_2 for materials qualification testing without needing to undertake $K_{1H-E1820}/K_{IH-E1681}$ testing.
  The gap closure plan for dealing with pipelines with low in-air CVN toughness (Gap 1.9) and a potential gap closure plan for microstructure (Gap 1.12) will be relevant here. See also Gap 2.3.
- *Gap 2.2 Fatigue (O):* Effect of static growth (da/dt effect) at higher levels of K_{max} which would influence the determination of ΔK_{th} is a gap.
  This gap is being studied in the following programmes: EPRG Project 232, the DNV JIP H2Pipe and DNV Integrity JIP.
- *Gap 2.3 Material testing (O):* There is a need to publish industry standard material testing protocols in H_2.
  This gap is being contributed to by EPRG Projects 232/231 and other numerous programmes including the DNV JIP's and HyBlend. This is a high priority gap to resolve.

Loading and operation in H_2 service

- *Gap 1.19 Gas composition (O):* Hydrogen limits and the use of inhibitor molecules to mitigate hydrogen embrittlement:
  National Grid is currently undertaking research on this topic. This is a subject of academic discourse with no apparent solution in sight, but Sandia's work on the role of oxide layers suggests this will unlikely be a solution. Other industry groups are also considering research on this topic.
- *Gap 1.21 Corrosion protection (internal and external coatings, clad layers, CP) (O):*
  The effect of hydrogen on existing corrosion mitigation methods is a gap.
  National Grid have initiated a research programme to look at the interaction between internal coatings and hydrogen. The HyLine JIP is also investigating the interaction between hydrogen and CP.
- *Gap 1.22 Inspection (O):* There is a gap on inspection in H_2 service. There are two proposed projects at present that may close this gap as follows:
- Pipeline Operating Forum is proposing to develop an appendix for H_2 service
  PRCi/EFI is proposing to set up a programme to look into crack detection inspection accuracy
- *Gap 1.24 Repairs (O):* there is a gap on how to repair defects in H_2 service:

Ongoing research led by Gasunie with HyTap project via EFI.

Outstanding gaps – gap closure plan to be defined

Degradation and defects

- *Gap 1.2 Planar defects (R):* Inspection tools should be qualified and tested to ensure that planar defects can be reliably detected if infield inspection data is used.
  Gap is open and can be closed either by operators, other research programmes or the Pipeline Operators Forum (POF) where defect acceptance criteria is more stringent than conventional hydrocarbon service.
- *Gap 1.5 Wrinkling/buckling/local deformation/large strain events (R):* There is a gap on the acceptability of wrinkles, buckling, local deformation and large strain events.
  Gap is open and can be closed by numerical/experimental programme.
- *Gap 1.6 Others (R):* There is a gap on the acceptability of other defects not discussed in the above sections.
  Gap is open and can be closed by cataloguing other defects and determining a gap closure plan.
- *Gap 2.6 Planar defects (R):* Determine appropriate planar defect size based on S-N tests or a suitable correction factor.
  Gap is open with no gap closure plan developed.

Material requirements and restrictions

- *Gap 1.8 Hardness (R):* There is a gap on hard spots and hard layers
  This can be closed by an experimental programme.
- *Gap 1.11 Grade (R):* An opportunity to potentially relax or eliminate the material performance factor, wall thicknesses below 1/4", limitations on UTS, use of higher grades, the influence for offshore conditions and possible contradictions in location class (Clause GR 5.2.1 (c) (1) allows only location class 3 and 4 to be used).
  It is suggested to first understand the basis (i.e., taking into account literature covering background to B31.12) and then proceed with research and/or mitigation actions such as bespoke H_2 material testing or other suitable evidence to relax/eliminate these requirements. The B31.12 committee may be investigating this, but the full remit nor timeliness is not understood at present.
- *Gap 1.13 Fracture arrest (running brittle fracture) – DWTT (R):*
  - Speed of running brittle fracture would probably be too quick for hydrogen to affect the resistance to running brittle fracture but this has not been proven and thus remains a gap.
  - The decompression curve of hydrogen is less onerous than natural gas (including blends). Considering the above, although not proven, it is felt that the likelihood of running brittle fracture is low if API-5L Annex G is followed; it is still a gap but considered of low priority.
- *Gap 1.15 Residual stress (R):* It is recommended that the requirement for PWHT for wall thicknesses greater than 20 mm be discussed with the jurisdictional authorities to determine if this can be revisited subject to closing this outstanding gap. A possible option to close the gap is to determine if a PWHT is warranted using ECA methods by calibrating the approach for smaller thickness using the results from EPRG Project 231/2. This should be done in conjunction with closing Gap 2.4. Irrespective of this, the DNV JIP H2Pipe may implicitly, or explicitly, address this since offshore pipelines will typically have wall thicknesses greater than 20 mm.

An explicit gap closure plan is required to address this or confirm that this is being explicitly addressed by the DNV H2Pipe JIP.

- *Gap 2.4 Residual stress (R):* Residual stress estimates proposed by PRCi, and Andrews and Slater [19] should be reviewed to provide less conservative residual stress estimates for an ECA. In addition, the gap closure plan from Gap 1.15 should be completed in partial fulfilment of this gap.
  This is an outstanding gap.
- *Gap 2.7 Fatigue (R):* Very limited S-N tests exist at present which potentially may be an issue for vintage pipelines.
  This is an outstanding gap that could be closed by an appropriate experimental programme.
- *Gap 2.8 Material testing (R):* For S-N tests there is a gap on test protocols for S-N curve testing.
  This is an outstanding gap that could be closed by an appropriate experimental programme.

Loading and operation in H_2 service

- *Gap 1.16 Loading (R):* Limiting pressure fluctuations. Although there is no requirement to limit ΔP, a simplified limit such as 30% of MAOP, or cycling limits from DVGW G464 may be advisable to generally align with the intent of Level 2 to limit pressure fluctuations.
  This is an outstanding gap that can be solved through a simplified analytical exercise using an appropriate ΔK_{th} (e.g. ΔK_{th} from DVGW G464) and engineering judgement to ensure a simplified Level is recommended. The recommendation does not have to be perfectly aligned with Level 2 since B31.12 does not have any fatigue limitation. Such limitations would be aimed at daily fluctuations as opposed to cycling due to unforeseen events, shutdowns, seasonal changes (inject / produce) etc. as long as the number of cycles for such events is low.
- *Gap 1.17 Integrity Management (R):* There is a gap in developing interim guidance on simplified assessment of common defects building on EPRG Project 221 and the ongoing gaps identified in the defect sections (Gaps 1.1 – 1.6).
  A plan is required to close this gap.
- *Gap 1.18 Gas Composition - Hydrogen limits and the use of inhibitor molecules (R):* Confirm EPRG view on the level of hydrogen blending above which there is a measurable impact on material performance, building on learnings from EPRG Project 231 & 232 and numerous JIP's e.g., DNV JIP H2Pipe (modern offshore materials).
  This is an outstanding gap.
- *Gap 1.20 Corrosion protection (internal and external coatings &clad layers) (R):* The impact of coatings & clad layers on mitigating hydrogen embrittlement is in general an outstanding gap.
- *Gap 1.23 Repairs (R):* A gap on managing repairs from previous service:
  There is an outstanding gap to establish which repairs are problematic in hydrogen, and to set simple screening criteria to determine whether a cut out and replacement is required without recourse to an ECA assessment.
- *Gap 2.5 Inspection (R)* There is a gap in developing a screening method for defects greater than the Level 2A ECA limits that will allow for targeted inspections.
  This is an outstanding gap.
- *Gap 2.9 Loading (R):* There is a gap to establish the loading limits based on an S-N approach.
  This is an outstanding gap.

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Appendix 1: Level 1

Theme	Guidance	Gaps and Closure Plan
Degradation and Defects		
Degradation	The impact of other degradation mechanisms, including interaction with H_2 embrittlement mechanisms, has to be considered separately and is out of scope of this document. **Commentary:** This Guideline only covers the impact of hydrogen on defects, i.e., the hydrogen embrittlement mechanism. Impact of other degradation mechanisms have to be assessed separately, and interaction with hydrogen must be considered. Level 1 is not suitable when interaction with other mechanisms is occurring.	For this situation, it is out of scope of this Guideline.
Weld Planar Defects	The following are general defect size recommendations which can be assumed as a starting defect in most cases (before any crack growth as a result of installation and operation of the pipeline prior to hydrogen service). The numeric values for these defect sizes should be confirmed by the operator based on the below taking into account defect specification at the time of construction and any actual recent inspection data. The acceptability of the defect size is subject to the gap closure plan. In the absence of other data, the following defect sizes are recommended to be used for both internal (conservatively) and surface breaking flaws. Longitudinal welds - modern pipe: Inspection data, NDE specifications otherwise N5/N10 notch depending on the original specification. [This is generally relevant for pipelines since 1994, when AUT NDT became available] - vintage pipe: Inspection data, specification at the time, and accuracy of the tool. - In absence of above a standard workmanship defect of 3 mm deep and 50 mm long is recommended Onshore Girth welds - Inspection data - NDE AUT-ToFD-PAUT specification - EPRG Girth Weld Defect Guidelines - In absence of above a standard workmanship defect of 3 mm deep and 50 mm long is recommended Offshore Girth Welds - Inspection data - NDE AUT-TOFD-PAUT specification - Vintage pipe: Workmanship defect based on Inspection data from the time (likely visual + x-ray (from 1970s/80s)	**Gap 1.1 (O):** Recommended defect size and the impact of hydrogen on internal defects. B31.12 does not cover gap explicitly. There is an EPRG Project 231 and 232 in progress to justify the proposed defect size guidelines. It is also important to understand the difference between embedded and surface breaking flaws. **Gap 1.2 (R):** Inspection tools should be qualified and tested to ensure that defects can be reliably detected if infield inspection data is used. Gap is open and can be closed either by operators, other research programmes or the Pipeline Operators Forum (POF) where defect acceptance criteria is more stringent that conventional hydrocarbon service.

	and manual ultrasonics/MPI (1990s)), specification at the time and accuracy of the tool - In absence of above a standard workmanship defect of 3 mm deep and 50 mm long is recommended **Commentary:** - There are no definitive guidelines on general defect size recommendations and the above are general recommendations to be confirmed by the operator. - A differentiation may be made between internal and surface breaking flaws, as well as ID vs OD flaws. Note the 3x50mm recommended assumption provided above is for both internal (conservative) and surface breaking flaws. There is an ongoing discussion as to the impact of hydrogen on buried flaws. - If recourse is made to infield inspection data the inspection tools should be suitably qualified. - For thin walled pipelines, typical for onshore pipelines, the EPRG girth weld defect limits exceed that of B31.12 option B and thus a check at level 2 should be conducted if the defect size starts becoming significant compared to the wall thickness and/or the loading starts becoming significant compared to Level 1 loading limits.	
Body Planar Defects	Use workmanship defect levels in API 5L at time of construction.	No gap
Volumetric Defects	Limit the net section stress to less than minimum yield (BS7910 Appendix P reference stress limit load equations or equivalent can be used for calculation) or set the flow stress (fu) to yield in DNV-RP-F101 until gap closure plan is completed. If defects are of significant depth, consideration may need to be given to other loading modes such as fatigue. **Commentary:** - The limit state for volumetric defects is primarily plastic collapse. The influence of H_2 would thus be confined to reduction in ductility. A first order estimate is to ensure that the net section stress is below yield where according to the EPRG literature review there is not a strong effect of H_2. - There is a gap to show that the DNV-RP-F101 equations or ASME B31G equations can be used as is or without knockdown factors. To relax this limitation then further experimental/numerical assessments should be undertaken.	**Gap 1.3 (O):** There is a gap to show whether ductility is influenced by H_2 below UTS, and hence plastic collapse. The volumetric flaw assessment procedures as per ASME B31G or DNV-RP-F-101 are based on UTS and yield strength. Gap is open and can be closed by numerical/ experimental programme (SafeH2Pipe).
Dents and Combinations of Mechanical Damage	- Allowable strain 2% for H_2 service for plain dents as per B31.12 (GR 5.6 and PL-3.7.5 (c)) subject to jurisdictional requirements and approval, for Option A and B. - If dent or dent/gouge has strain greater than 2%, or contains planar defects or contains a hardened layer then a	**Gap 1.4 (O):** There is a gap on the acceptability of dents or dent/gouge combinations beyond

	Level 3 analysis should be conducted using H_2 affected material properties in a fracture mechanics analysis, or repaired, until gap closure plan is completed. **Commentary:** - The acceptability of dents and dent/gouge combinations under H_2 service has not been extensively studied with a lack of full scale testing, which is important since current methodologies are empirical in nature, and is thus considered a gap.	current B31.12 limits. Gap is open and can be closed by numerical/experimental programme (SAFEH2Pipe).
Wrinkling/ buckling/ local deformation/ large strain events	At present there is no recommendation for wrinkling/buckling or cases of local deformation or large strain events. Apart from removal / repair, the only recourse is to model using H_2 material data in any stress/fracture mechanics analysis although acceptability limits, similar to dents, will be constrained by the reduction of ductility under H_2 service. **Commentary:** The acceptability of wrinkling, buckling, local deformation and large strain events has not been extensively studied and is thus considered a gap.	**Gap 1.5 (R):** There is a gap on the acceptability of wrinkles, buckling, local deformation and large strain events. Gap is open and can be closed by numerical/experimental programme.
Others	At present there are no recommendations for defects except those considered above and would require a Level 3 FFS assessment using H_2 affected material properties. **Commentary:** The acceptability of other defects has not been studied and is thus considered a gap.	**Gap 1.6 (R):** There is a gap on the acceptability of other defects not discussed in the above sections. Gap is open and can be closed by cataloguing other defects and determining a gap closure plan.
Material Requirements and Restrictions		
Hardness	- The B31.12 hardness requirement of 235 HV10 as per Table GR-3.10-1 (PL 3.19.8 - 237 BHN for production welds) is recommended to be revisited with jurisdictional authorities to consider relaxing these limits to 275HV10 (average), with a maximum hardness of 300HV10. This recommendation is based on limited data and may be revisited pending the results of ongoing testing. - B31.12 does not allow "metallurgical notches" (similar to hard spots) and currently there is no recommendation for hard spots or hard layers. B31.12 is more restrictive for gaseous hydrogen than NACE MR0175 / ISO 15156 is for sour service. This restriction does not appear to be justified and it is recommended to be discussed with jurisdictional authorities if this can be revisited to align with the general hardness guidelines provided above.	**Gap 1.7 (O):** The impact of higher levels of hardness on material properties in H_2 The gap is open but plan is in place and being executed: EPRG Projects 231 and 232 are looking at hardness effect on fatigue crack growth and fracture toughness (normal and high hardness girth welds) and difference in microstructure. The EPRG projects are

	Commentary: - Currently natural gas pipelines can see hardness up to 350 HV10. There are several research programmes ongoing to ascertain if the material properties (toughness, ductility, fatigue) in H_2 are substantially different from material properties at lower hardness Levels (235 HV10). - Initial data published recently, namely the SyWest H2 report [20] and preliminary results from EPRG Projects 231 and 232 suggests that the existing hardness requirements within B31.12 are unnecessarily conservative. Further evidence is currently being gathered as part of an ongoing gap closure plan to fully justify a relaxation of these limits. - As discussed in the microstructure and chemical composition aspect (Gap 1.12) the hardness limitations are more severe than that for sour service whereas it would be expected that sour service rated material should give higher confidence as to the performance in hydrogen based on general improved quality of steel. ISO 15156 [21] allows 300HV10 in the level 1 sour service regime. The equivalence point between H_2 and H_2S conditions is still being researched. - Hard spots (through thickness) in parent pipe and "metallurgical notches" are not allowed according to B31.12 and are considered a gap but this is already an issue for natural gas service. Hard layers are not referenced in B31.12 and are considered a gap, again this is already an issue for natural gas service.	testing a 1970's X60 pipe with two girth welds (one from the original construction and one new manual cellulosic weld), and a 2021 X70 pipe with two mechanised girth welds, one "normal" and one deliberately aiming for high hardness. In addition, there are multiple other projects which are testing a wide range of different materials, including two DNV JIPs and a programme initiated by the H_2 Fuel Task Group in API 1104 (see also Gap 1.12). **Gap 1.8 (R):** There are gaps regarding the effect of hydrogen on localised hard areas, including hard spots (as defined in API 5L), hard layers and "metallurgical notches" as defined in B31.12. There is no specific testing programme planned as yet. Additional testing may be required to address the acceptability of the 3 separate phenomena.
Air Toughness (CVN)	- ASME B31.12 PL-3-7.1 (b) (1) (-a) is incorrect and should probably be referring to the CVN requirements (including shear) in Table 8 in Section 9.8.2.2, and Section 9.8.2.3, of API 5L. - Vintage lines that meet the CVN requirements of Section 9.8.2.2 and Table 8 are recommended to be considered to meet the CVN requirements of B31.12 subject to jurisdictional requirements/approval.	**Gap 1.9 (O):** How to manage vintage welds with low toughness in air. Initial research suggests performance is similar to modern materials with higher toughness, but there is a gap closure

	- For vintage lines that have lower CVN toughness levels than Table 8 this is currently the subject of a gap closure plan. **Commentary:** - It is assumed that for vintage lines, when CVN requirements in API 5L did not exist, that compliance to Table 8 and the relevant shear requirements based on local or company specifications at the time is sufficient to meet the intent of B31.12. - For vintage lines that have lower CVN toughness levels than Table 8 this is currently the subject of a gap closure plan, although recent publications [20, 22] do suggest there is not a correlation between CVN toughness in air and fracture toughness in hydrogen.	plan that is presently being executed. The following research programmes are addressing this issue: - SyWest H2 - DNV integrity JIP, and - HyBlend (amongst others)
H_2 Fracture Toughness	If toughness and shear levels of Table 8 in Section 9.8.2.2, and Section 9.8.2.3, of API 5L and 275 HV10 average hardness restrictions (See above discussion on Hardness) are met then no H_2 fracture toughness testing is required.	Potential gaps are covered in Hardness and Air Toughness (CVN) requirements (Gap 1.7, 1.8 & 1.9)
Ductility	- No additional requirements are needed for stress-based designs. - For designs or situation where the strain exceeds the yield strain (e.g. strain based design, possible offshore loading, or in the vicinity of defects) bespoke tensile testing in H_2 as per ASTM G129 [23] or equivalent should be conducted. - Acceptance limits for allowable strains for design are governed by the applicable design code and for strains at defects the acceptance limits are defined in the defect requirement section. **Commentary:** - At present evidence suggests that the effect of H_2 is focused on reduction of elongation, mainly between UTS and failure. Currently most defect assessment methodologies and strain-based design codes have strain acceptance limits (explicit and implicit) between yield and UTS and potentially may be impacted by such restrictions. This is considered a gap.	Potential gaps arecovered in assorted defect requirements (Gap 1.1 – 1.6).
Fatigue	- There is no B31.12 Option A fatigue testing requirement **Commentary:** - Although there is no requirement for fatigue testing nor a requirement limiting ΔP (or equivalent longitudinal Ds) except through reduced design factor, it is recommended to limit the extent of ΔP such that the $\Delta K < \Delta K_{th}$ as per gap for loading (Gap 1.16) and to align with Level 2.	Potential gaps are covered in loading requirement gap closure plan Level 1 (Gap 1.16).
Material Testing	- No specific H_2 material testing is required for B31.12 Option A.	**Gap 1.10 (O):** There is a gap on developing common

	- The requirement to dig up every mile and confirm material properties (yield, UTS, hardness, inspection of samples for defects etc.) should either be conducted or be discussed with the jurisdictional authorities to determine if this can be revisited if there is sufficient statistical evidence to make a grouping of linepipe with similar material properties subject to closing a gap underpinning this subject to jurisdictional requirements/approval. See sections on fracture toughness, fatigue and ductility on when it is possible to take conservative lower bound values from literature results on similar materials. **Commentary:** There is an outstanding gap on developing common groupings (e.g. microstructure, grade, vintage, manufacturing method etc.) of similar and existing H_2 material test results in a statistically appropriate manner for using in ECA assessments and to waive requirements for determining material performance data by dig ups in determining grouping subject to jurisdictional requirements/approval.	groupings based on for example microstructure, grade, vintage, manufacturing method etc. This gap is being worked, and numerous ongoing JIP's will provide input into developing common groupings. It is a high priority gap to resolve.
Grade	B31.12 allows Option A to be used for SMYS up to 70 ksi. **Commentary:** - It should be noted the materials performance factor will impact the allowable design factor for grades above X52. - A potential gap is understanding the justification for material performance factor and itemising what aspects have to be addressed to relax this requirement.	**Gap 1.11 (R):** An opportunity to potentially relax or eliminate the material performance factor, wall thicknesses below 1/4", limitations on UTS, use of higher strength grades (including for welds), the influence for offshore conditions and possible contradictions in location class (Clause GR 5.2.1 (c) (1) allows only location class 3 and 4 to be used). Suggest to first understand the basis (i.e., considering literature covering background to B31.12) and then proceed with research and/or mitigation actions such as bespoke H_2 material testing or other suitable evidence to

		relax/eliminate these requirements.
Yield Strength	B31.12 does not include restrictions on actual yield strength beyond current API-5L. **Commentary:** For girth welds, combined with the potential planar defect gap closure plan, the weld yield strength recommendations in the EPRG guidelines on acceptance of girth weld defects is preferable.	Potential gaps are covered under planar defect gap closure plan (Gap 1.1 and 1.2).
UTS	- B31.12 Option A restricts actual UTS to 100 ksi and it is recommended to discuss this with the jurisdictional authorities to determine if this can be revisited such that this can be relaxed to the API 5L requirement of 110 ksi subject to a gap closure plan into understanding the basis of the limitations and developing mitigation actions such as bespoke H_2 material testing or other suitable evidence subject to jurisdictional requirements/approval. - B31.12 Option A restricts weld metal strength to 100 ksi and it is recommended to remove this requirement to align with API 5L, subject to a gap closure plan and jurisdictional requirements/approval. **Commentary:** The assumption is the restriction of 100 ksi is on actual UTS. Currently API 5L allows UTS up to 110 ksi for X52 to X70 although in the past there was not such a restriction in API 5L and thus pipelines meeting API 5L requirements may not necessarily meet B31.12 Option A. This limitation is currently a gap in concert with the understanding of the limitations on higher grades and material performance factors and what mitigation/research can be done to relax such requirements.	Gap is covered under grade (Gap 1.11).
Microstructure and chemical composition	The Non-Mandatory Appendix G is recommended not to be followed. See sections on fracture toughness, fatigue and ductility on when it is possible to take conservative lower bound values from literature results on similar materials. **Commentary:** - Most vintage lines will not meet the requirements of Non-Mandatory Appendix G. Furthermore, meeting Appendix G is in direct conflict to Annex A of ISO 3183 (European Onshore Gas Lines) and is more restrictive than Annex H of API 5L (sour service requirements) and the EIGA guideline Appendix D for H_2. Although there is not a direct equivalence between H_2 and H_2S environments, reusing a sour rated pipeline should give higher confidence as to the performance in hydrogen based on general improved quality of steel.	**Gap 1.12 (O):** **Microstructure.** There is a gap with respect to the recommendations of non-mandatory Appendix G of B31.12 and existing pipe materials, and with respect to the requirements of Annex A of ISO 3183 and Annex H of API 5L. To address this gap, and to assess whether $K_{IH-E1820}/K_{IH-E1681}$ ever falls significantly below 60 MPa√m, EPRG projects

	- Microstructure may have an influence on H_2 material properties and without recourse to H_2 material testing at Level 1 there may be possibility of inclusion of susceptible microstructures and identification of such is the subject of a gap closure plan.	231 and 232 are ongoing, together with numerous other projects (for example the DNV JIP H2Pipe and the DNV Integrity JIP and the SyWest H2 project [20]). These projects are testing a wide range of existing pipes of different ages and manufacturing routes. General types of parent material microstructures which will need to be assessed include, but are not limited to: • As rolled / normalised ferritic / pearlitic steels, more common in older or lower grade EW pipes • TM rolled ferritic / pearlitic, more common onshore • TMCP ferritic / pearlitic, more common offshore • TMCP ferritic / bainitic, lean chemistry more common offshore or where sour resistance is required • Q&T, more common in seamless pipes. A separate classification will be required for the seam and girth welds if these have average hardness over 275 HV10.
Fracture arrest (running	API 5L DWTT requirements, at the time of construction, are recommended in place of the less conservative B31.12 DWTT requirements. **Commentary:** B31.12 DWTT are less onerous than API 5L. Most operators	**Gap 1.13 (R):** • Speed of running brittle fracture would probably be too quick for

brittle fracture) - DWTT	have pipelines designed to API 5L or equivalent and thus from a pragmatic and additional process safety perspective it is recommended to follow API 5L.	hydrogen to affect the resistance to running brittle fracture but this has not been proven and thus remains a gap. • The decompression curve of hydrogen is less onerous than natural gas (including blends). Considering the above, although not proven, it is felt that the likelihood of running brittle fracture is low if API-5L Annex G is followed, it is still a gap but considered of low priority.
Fracture arrest (running ductile fracture) - CVN	It is recommended to determine CVN requirements as per API 5L Appendix G.9 Battelle Two Curve Model Approach, **Commentary:** The crack driving force will be greater in natural gas than for hydrogen because the decompression speed of running ductile fracture would probably be too quick for hydrogen to affect the resistance to running ductile fracture but this has not been proven and thus remains a gap.	**Gap 1.14 (O):** • Speed of running ductile fracture would probably be too quick for hydrogen to affect the resistance to running ductile fracture but this has not been proven and thus remains a gap • The decompression curve of hydrogen is less onerous than natural gas (including blends) Considering the above, although not proven, it is felt that the likelihood of running ductile fracture is low if API-5L Annex G is followed, it is still a gap but considered of low priority.

		This is also being investigated by the DNV H2Pipe JIP.
Residual stresses	For wall thicknesses greater than 20 mm, where PWHT is required, a Level 2 assessment is recommended, or the requirement should be discussed with the jurisdictional authorities to determine if this can be revisited subject to a gap closure plan that shows that as welded residual stresses are comparable to PWHT or parent material residual stress Levels. **Commentary:** - Onshore natural gas transmission pipelines typically have a wall thickness less than 20 mm and thus this requirement is not relevant. - Offshore lines typically may have wall thicknesses greater that 20 mm and the requirement of PWHT has not been done or would not be practical to conduct for repurposing existing pipelines and thus a Level 2 or 3 assessment is required which considers residual stresses. Otherwise, this is a gap that could be closed by investigating the residual stresses in various wall thicknesses under differing conditions (as-welded versus PWHT and different welding methods and heat input etc.) and parent versus weld metal and the effect of thickness (less and greater than 20 mm).	**Gap 1.15 (R):** It is recommended that the requirement for PWHT for wall thicknesses greater than 20 mm be discussed with the jurisdictional authorities to determine if this can be revisited subject to closing this outstanding gap. A possible option to close the gap is to determine if a PWHT is warranted using ECA methods by calibrating the approach for smaller thickness using the results from EPRG Project 231/2. This should be done in conjunction with closing Gap 2.4. Irrespective of this, the DNV H2Pipe JIP may implicitly, or explicitly, address this since offshore pipelines will typically have wall thicknesses greater than 20 mm. An explicit gap closure plan is required to address this or confirm that this is being explicitly addressed by the DNV H2Pipe JIP.
Loading and Operations in H_2 service		
Loading	- The following are the static pressure recommendations for Level 1 as per B31.12 Option A: *Onshore:* *Hoop loading:* up to B31.12 Option A limits *Axial loading:* up to equivalent of B31.12 Option A hoop stress limits *Offshore:* same requirements as onshore	**Gap 1.16 (R):** Limiting pressure fluctuations. Although there is no requirement to limit ΔP, a simplified limit such as 30% of MAOP, or

	- B31.12 Option A does not have any limitations on ΔP but a generic limit may be advisable, such as 30% of MAOP or equivalent in longitudinal stress and can be the subject of an industry gap closure plan but at present is an outstanding potential gap. **Commentary:** - B31.12 is aimed primarily at onshore gas transmission pipelines and this recommendation is to make it inclusive to offshore pipelines. - Although there is no requirement to limit ΔP except through a reduced design factor, it is recommended to limit and monitor the extent of ΔP (or equivalent in terms of longitudinal stress) such that the $\Delta K < \Delta K_{th}$ and to align with Level 2. (See notes for Fatigue Level 1 and recommendations related to Operational pressure monitoring).	cycling limits from DVGW G464 may be advisable to generally align with the intent of Level 2 to limit pressure fluctuations. This is an outstanding gap that can be solved through a simplified analytical exercise using an appropriate ΔK_{th} (e.g. ΔK_{th} from DVGW) and engineering judgement to ensure a simplified level is recommended. The recommendation does not have to perfectly align with Level 2 since B31.12 does not have any fatigue limitation.
Design factors and derating factors, including location classes (onshore) and freespan / longitudinal stresses and cyclic loading (offshore)	- It is recommended to use the design factors in B31.12 but there is a potential gap looking into relaxing these restrictions. - It is recommended to discuss with the jurisdictional authorities to determine if clause PL 3.7.1(b)(5) from B31.12 that limits wall thickness to greater than 1/4", subject to gap closure plan can be revisited. **Commentary:** Other jurisdictions are still limited to using B31.12 Option A knock down factors including IGEM TD/1.	See gap closure plan under Grade (Gap 1.11).
Loading limitation due to static crack growth (da/dt)	- The axial/hoop stress is recommended to be less than K_{max} (i.e. the point at which static crack growth initiates, rather than K_{1H}/catastrophic fracture) and is the subject of an outstanding gap closure plan. - Offshore lines, or onshore lines subject to stresses above those induced by pressure, should take into consideration spanning, riser loading, geotechnical loading etc. in the longitudinal direction and should be accounted for in the longitudinal stress calculation.	See gap closure plan under Fatigue Level 2A. (Gap 2.2).
Failure modes/limit	*Onshore:* pressure loading only. If there is longitudinal loading beyond half the hoop stress, treat as an offshore line. *Offshore:* As per DNV-ST-F101 or API RP 1111 [24].	No gap.

states linked to environment e.g., onshore versus offshore	**Commentary:** If longitudinal loading is above the limits prescribed in the loading aspect for failure modes in DNV-ST-F101 or API RP1111 then Level 2 or 3 may be required and for more severe loading then there is an outstanding gap (Gap 1.5) under wrinkling/buckling/local deformation/large strain events aspect. Fatigue loading due to wave loading and/or vortex induced vibration would require a Level 2 or 3 assessment and be included in the fatigue assessment	
Operations e.g., pressure monitoring	The following recommendations are in addition to any jurisdictional requirements. - Where a ΔP limit is defined (see Loading Recommendations for Level 1), it is recommended that the company set a ΔP exceedance limit based on the original fatigue assessment, whereby the total ΔP (not partial pressure) and date is recorded. - In addition, it is recommended to specify a timely reassessment interval to determine if fatigue failure is an issue cognizant of such reassessments may provide input into ILI/inspection planning. - For offshore lines and pipelines subject to large strain events (e.g., geotechnical), additional monitoring is recommended. **Commentary:** DVGW G464 for onshore transmission lines: each pressure above 2 bar needs to be recorded, every 5 years reassess line (due to be published Q1 2023).	There may be a potential gap here on K_{max}, see Fatigue Level 2A (Gap 2.2)
Integrity Management	For defects that fall outside of the limits prescribed in the defect section, an assessment should be conducted according to PDAM or ECA procedures (BS7910, API-579, etc.) determining the appropriate limit states and the influence of H_2 material properties relevant to those limit states subject to an ongoing gap closure plan. An interim simplified assessment methodology is an outstanding gap without recourse to detailed ECA assessments. **Commentary:** There is presently no simplified guidance building on EPRG Project 221 to determine if interim assessment advice can be developed by looking at common defects and ascribing the appropriate limit state and the relevant H_2 material property and developing interim guidance e.g., corrosion defects will have a plastic collapse limit state with the only relevant H_2 material property is ductility. As ductility under H_2 conditions may not be as deleterious as originally thought, so simplified knockdown factors may be able to be generated pending ongoing JIP's and research programmes delivering more authoritative advice.	**Gap 1.17 (R):** There is a gap in developing interim guidance on simplified assessment of common defects building on EPRG Project 221 and the ongoing gaps identified in the defect sections (Gaps 1.1 – 1.6). A plan is required to close this gap.

Gas Composition (H_2 limits and the use of inhibitor molecules)	- It is recommended that any intentional addition of H_2 is considered as a hydrogen service pipeline and is the subject of this Guideline. - It is not recommended to rely on inhibitor molecules such as oxygen, carbon monoxide or carbon dioxide to mitigate the effect of hydrogen on material properties, subject to evidence to the contrary. **Commentary:** - There is no common EPRG view on the lower bound ppH_2 or $\%H_2$ limit at which material properties are affected by H_2 (<3%/6%/10%), this is an outstanding gap. - There are differing jurisdictional and code requirements whilst literature suggests that any level of H_2 may have a deleterious effect. - Partial pressure of hydrogen compared to the total pressure of the system should be used in place of blend percentage. - Irrespective of whether inhibitor molecules have a mitigating impact on hydrogen embrittlement in the long term or not (which is currently the subject of ongoing research), the current EU hydrogen quality specification does not allow levels of impurities to the concentration that would be required based on current literature. Note the EU specification is different to the currently proposed UK specification.	**Gap 1.18 (R):** Confirm EPRG view on the level of hydrogen blending above which there is a measurable impact on material performance, building on learnings from EPRG Project 231 and 232 and numerous JIP's e.g. DNV H2Pipe JIP (looking at modern offshore materials). This is an outstanding gap. **Gap 1.19 (O):** The use of inhibitor molecules to mitigate hydrogen embrittlement. National Grid is currently undertaking research on this topic. This is subject of academic discourse with no apparent solution in sight, but recent work on the role of oxide layers suggests this will unlikely be a solution. Other industry groups are also considering research on this topic.
Corrosion protection (internal and external coatings, clad layers, cathodic protection (CP))	- Internal coatings are not recommended to be used to mitigate hydrogen embrittlement, subject to evidence to the contrary. - It is not recommended to use prior evidence of performance under CP to represent hydrogen performance, unless evidence to the contrary is available. - The effect of hydrogen on existing corrosion mitigation methods (external corrosion coatings, CP, clad layers) is unknown, although seems unlikely to be a major risk, based on the low levels of hydrogen diffusing through the steel. These uncertainties should be accounted for in inspection programmes to ensure corrosion mitigation is maintained. **Commentary** - Internal coatings: It is unknown what impact the	**Gap 1.20 (R):** The impact of coatings & clad layers on mitigating hydrogen embrittlement is in general an outstanding gap. **Gap 1.21 (O):** The effect of hydrogen on existing corrosion mitigation methods is also a gap. National Grid have initiated a research programme to look at the interaction between internal

	increased velocities anticipated in H_2 will have on internal flow coatings. - External coatings: It is not known what impact diffusing H_2 will have on external coatings, or what impact external coatings will have on the diffusion of hydrogen. - Clad layers: There is much less data available on the performance of stainless steels in hydrogen, and remaining uncertainties on the fracture mechanics of clad layers. There are several ongoing EPRG programmes looking at this topic, but the performance of clad pipes in hydrogen remains a gap. - CP: Failures have been reported in various jurisdictions. - CP: B31.12 assumes no difference between hydrogen and natural gas, however the potentially additive interaction between hydrogen and CP is a gap that should be closed.	coatings and hydrogen. The HyLine JIP is also investigating the interaction between hydrogen and CP.
Inspection (Preparation for H_2 service and inspections once H_2 service has commenced)	*Preparation for H_2 service:* It is recommended to establish the baseline condition of the pipeline using suitable evidence that may include manufacturing construction records (weld defects etc.), operational history and previous inspection records (corrosion, dents etc.). If defects are above or cannot be demonstrated to be within those established in Level 1 of this Guideline, then it is recommended to conduct an inspection. *In H_2 service:* It is recommended that inspection requirements in terms of type and frequency be as per local pipeline integrity management standards, taking into account the deleterious effects of H_2 on material properties and the current state of the pipeline, and the operational regime (e.g., pressure fluctuations as captured in the Level 1 Loading section of this Guideline). **Commentary:** - Inspection verification typically will be more sophisticated than previously required (e.g., planar defect detection) and this is an outstanding gap. - The inspection of planar defects to the accuracy potentially required is an outstanding gap (See Gap 1.2)	**Gap 1.22 (O):** There is a gap on inspection in H_2 service. There are two proposed projects at present that may close this gap as follows: Pipeline Operating Forum is proposing to develop an appendix for H_2 service PRCi/EFI is proposing to set up a programme to look into crack detection inspection accuracy
Repairs	*Previous repairs:* It is recommended, as per B31.12, to cut out and replace previous repairs unless it can be justified by an ECA of the defect and repair methodology (following the principles discussed elsewhere in this guideline) that it is acceptable or to use a simple screening criteria, but the latter is an outstanding gap subject to jurisdictional requirements/approval. *Repairs in H_2 Service:* This is a gap, including hot taps in H_2 service. **Commentary:** *Previous repairs:* Some defects that were repaired, subject	**Gap 1.23 (R):** A gap on managing repairs from previous service. There is an outstanding gap to establish which repairs are problematic in hydrogen, and to set simple screening criteria to determine whether a cut out and

	to the repair technology used, are less deleterious than others in H_2 service (e.g. planar defects compared to external corrosion) and cut out and replacement of such less deleterious defects may be onerous.	replacement is required without recourse to an ECA assessment. **Gap 1.24 (O):** There is a gap on how to repair defects in H_2 service: Ongoing research led by Gasunie HyTap project via EFI.

Appendix 2: Level 2A

Theme	Guidance	Gaps and Closure Plan
Degradation and Defects		
Degradation	The impact of other degradation mechanisms, including interaction with H_2 embrittlement mechanisms, has to be considered separately and is out of scope of this document. **Commentary:** This Guideline only covers the impact of hydrogen on defects, i.e., the hydrogen embrittlement mechanism. Impact of other degradation mechanisms have to be assessed separately, and interaction with hydrogen must be considered. Level 2A is not suitable when interaction with other mechanisms is occurring.	For this situation, it is out of scope of this Guideline.
Planar Defects	As for Level 1	As for Level 1
Body Planar Defects	As for Level 1	As for Level 1
Volumetric Defects	As for Level 1	As for Level 1
Dents/Combinations	As for Level 1	As for Level 1
Wrinkling/buckling/local deformation/large strain events	As for Level 1	As for Level 1
Others	As for Level 1	As for Level 1
Material Requirements and Restrictions		
Hardness	As for Level 1	As for Level 1
Air Toughness (CVN)	As for Level 1	As for Level 1
H_2 Fracture Toughness	- ASME B31.12 PL 3.7.1 (b) (2) requires $K_{IH\text{-}E1681}$ testing as per ASTM E1681. It is recommended to replace E1681	**Gap 2.1 (O):**

	with testing as per ASTM E1820 especially where fracture mechanics calculations are required. Testing may be waived if material does not exceed Level 1 hardness limits and it can be justified by suitable evidence that the pipe meets the required K_{IH}. For example, a conservative lower bound value of material toughness in hydrogen could be used from available literature (such as B31.12 or SyWestH2 [20]) provided the operator is able to demonstrate that they are comparing like for like. It is recommended that the substitution, or alternative evidence, be discussed with the jurisdictional authorities if this is acceptable. - If E1681 is used in the spirit of a qualification test, without extensive fracture mechanics calculations (with the aim of ensuring that the threshold stress intensity factor meets 50 ksi√in) and the pipeline meets all other requirements of B31.12, then this test is acceptable although the requirement should be discussed with the jurisdictional authorities to determine if the linear elastic limitation inherent in ASTM E1681 can be revisited if applicable. **Commentary:** Presently CVN is not considered a suitable concept to determine material toughness in hydrogen subject to the gap closure plan for toughness (CVN). Modern pipeline steels are very unlikely to meet all the K_{1H} test requirements of B31.12 PL 3.7.1 (b) (2), which references KD-10 from ASME BPVC Section VIII Division 3 [25], and thus requires a constant displacement or constant load test following ASTM E1681, where K_{IAPP} should be equal or higher to 50 ksi√inch. ASME BPVC is written around pressure vessels and not pipelines, therefore there are various discrepancies between these requirements and pipeline steels. For example, for constant displacement (bolt loaded) specimens, if subcritical crack extension is not observed [see KD-1047(b)], then K_{IH} is equal to 50% of K_{IAPP}, in which case K_{1APP} has to be at least 100 ksi*inch$^{1/2}$ (or ~110 MPa*m$^{1/2}$). However, ASTM E1681 is based on linear elastic fracture mechanics principles and for modern linepipe steels 110 MPa*m$^{1/2}$ will likely be in the elastic plastic region and not meet the validity criteria. Notwithstanding this if ASTM E1681 is purely used as a qualification test, without recourse to fracture mechanics calculations involving toughness and the pipeline meets all other requirements of B31.12, then this test	There is a gap to develop simplified recommendations on toughness performance in H_2 for materials qualification testing without needing to undertake $K_{1H-E1820}$/$K_{IH-E1681}$ testing. The gap closure plan for dealing with pipelines with low in-air CVN toughness (Gap 1.9) and a potential gap closure plan for microstructure (Gap 1.12) will be relevant here. See also Gap 2.3. This is a high priority gap to resolve.

	may be acceptable although waivers may be required for some of the specific validity criteria.	
Ductility	As for Level 1	As for Level 1
Fatigue	- Use Sandia/B31.12 curves [1, 16] or conduct fatigue testing as per ASTM E647 if pipeline-specific data is required. - Deriving a ΔK_{th} from Paris-Erdogan fatigue test curves may be subject to the influence of K_{max} resulting in potential crack growth under a static load (da/dt) and this is a gap being covered by a gap closure plan. **Commentary:** - Recent fatigue tests at low ΔK show that there is a static load crack growth effect (da/dt) at higher Levels of K_{max} and this should be considered in defining ΔK_{th} and is the subject of ongoing research.	**Gap 2.2 (O):** Effect of static growth (da/dt effect) at higher Levels of K_{max} which would influence the determination of ΔK_{th} is a gap. This gap is being studied in the following programmes: - EPRG Project 232 - DNV H2Pipe JIP and DNV integrity JIP
Material Testing	- The recommendations for H_2 material testing should follow one of the two options or a combination thereof: a) Fracture toughness (ASTM E1820 or E1681 or equivalent), ductility (ASTM G129 or equivalent) and fatigue (ASTM E647 [26] or Sandia/ASME B31.12 fatigue curves [1, 16] or equivalent) material testing as per ANSI/CSA CHMC 1-2014 [27] or equivalent protocols subject to closure of gaps on material testing. b) Material properties from equivalent materials previously conducted subject to closure of gap on material property grouping - The requirement to dig up every mile and confirm material properties (yield, UTS, hardness, inspection of samples for defects etc.) should either be conducted or waived if there is sufficient statistical evidence to make a grouping of linepipe with similar material properties subject to closing a gap underpinning this subject to jurisdictional requirements/approval. **Commentary:** The following are gaps with regards to material testing as part of an existing gap closure plan: - Defined H_2 material test protocols including specification on how to control test environment (particularly O_2 and H_2O). - Correlation between gaseous and electrochemical charging methods The following are gaps that have to be addressed on using small scale test results to provide assurance of overall pipeline integrity: - Overconservatism of rules based on small scale tests - Relationship of CVN Levels in air in predicting behaviour under H_2 conditions As also discussed in Level 1	**Gap 2.3 (O):** There is a need to publish industry standard material testing protocols in H_2. This gap is being contributed to by EPRG Projects 232/231 and other numerous programmes including the DNV JIP's and HyBlend. This is a high priority gap to resolve. See also Gap 2.1. The gap on developing common groupings based on for example microstructure, grade, vintage, manufacturing method etc. is covered in Level 1 Material Testing (Gap 1.10). The gap on conservatism and relationship of small-scale test data is covered in the assessment of defects section (Gap 1.1-1.6).

	Materials Testing, there is an outstanding gap on developing common groupings (e.g. microstructure, grade, vintage, manufacturing method etc.) of similar and existing H_2 material test results in a statistically appropriate manner for using in ECA assessments and to waive requirements for determining material performance data by dig ups in in determining grouping subject to jurisdictional requirements/approval.	
Grade	B31.12 Option B allows the use of grades up to X80. See Level 1, Gaps 1.10 and 1.11.	No gap.
Yield Strength	As for Level 1	As for Level 1
UTS	- B31.12 Option B is compliant with API 5L on UTS of parent pipe for grades up to and including X80 but for higher grades, this is a gap. - B31.12 Option B restricts weld metal strength to 110 ksi and it is recommended to remove this requirement to align with API 5L, subject to a gap closure plan.	- For grades greater than X80 the gap plan under Level 1, Grade, should be completed (Gap 1.11). - For weld metal the gap plan under grade should be completed (Gap 1.11).
Microstructure and chemical composition	PL 3.7.1 (2)(-b) states that the phosphorus content shall not exceed 0.015% and pipeline mill shall be manufactured with inclusion shape controlled practices. It is recommended to confirm with the jurisdictional authorities whether this can be revisited, as long as material testing per 2A or equivalent (such as the SyWest H2 data [20]) shows no deleterious effects under H_2 service. And also: As for Level 1	No gap.
Fracture arrest (running brittle fracture) - DWTT	As for Level 1	As for Level 1
Fracture arrest (running ductile fracture) - CVN	As for Level 1	As for Level 1
Residual stresses	Residual stress profiles (actual or industry recommended guidelines) should be used in any ECA. More definitive recommendations on residual stress profiles are the subject of a gap closure plan. **Commentary:** Residual stress profiles recommended by BS7910 for as welded weldments may be overly conservative whilst there are recommendations from PRCi and published literature (Slater et al.) in conjunction with current H_2 testing projects that may provide more definitive, less conservative guidance.	**Gap 2.4 (R):** Residual stress estimates proposed by PRCi and (Slater et al.) should be reviewed to provide less conservative residual stress estimates for an ECA. This is an outstanding gap. In addition, the gap closure plan from Level 1

		should be completed (Gap 1.15).
Loading and Operations in H_2 service		
Loading	The following are the static and cyclic pressure loading recommendations: *Onshore:* Pressure cyclic hoop loading: permissible loading will be defined by $\Delta K<\Delta K_{th}$ for planar defects (See notes for Fatigue Level 1). For other defects, load limits defined in Level 1. Pressure cyclic axial loading: limited to half hoop stress Static hoop loading: $K_{max}<K_{th}$ which is the subject of an ongoing gap closure plan Static axial loading: as for hoop loading; defect size may be different and stress will typically be half that for hoop loading. *Offshore:* Pressure cyclic hoop loading: as for onshore Pressure cyclic axial loading: as for onshore + wave loading, VIV etc. Static hoop loading: as for onshore Static axial loading: to include pressure loading, riser/spanning loading, geotechnical loading, fabrication/installation stresses/strains etc. Principal stresses must be less than or equal to max Option B loading (0.72 * yield) **Commentary:** ΔK_{th} may be dependent on K_{max} which will further limit the allowable static hoop loading and is the subject of an ongoing gap closure plan.	- The gap on ΔK_{th} and a possible new K_{max} limitation is covered under the Fatigue gap plan in Level 2A (Gap 2.2). - The gap on design factors (material performance factors etc.) is covered under the Level 1 Grade gap closure plan (Gap 1.11).
Design factors and derating factors, including location classes (onshore) and freespan / longitudinal stresses and cyclic loading (offshore)	As for Level 1	As for Level 1
Loading limitation due to static crack growth (da/dt)	As for Level 1	As for Level 1

Failure modes/limit states linked to environment e.g. onshore versus offshore	As for Level 1	As for Level 1
Operations e.g. pressure monitoring	As for Level 1	As for Level 1
Integrity Management	As for Level 1	As for Level 1
Gas Composition (H_2 limits and the use of inhibitor molecules)	As for Level 1	As for Level 1
Corrosion protection (internal and external coatings, clad layers, CP)	As for Level 1	
Inspection (Preparation for H_2 service and inspections once H_2 service has commenced)	*Preparation for H_2 service:* ILI or other suitable inspection technology to detect defects greater than the Level 2A ECA limits followed by repair or other suitable mitigation measures. *In H_2 Service:* ILI or other suitable inspection technology to detect defects greater than the Level 2A ECA limits followed by repair or other suitable mitigation measures where frequency should take into account any exceedance of the established pipeline operating envelope. There is a potential gap in developing a screening method followed by targeted inspections in addition to the outstanding gap on H_2 inspection as per Level 1. **Commentary:** There is significant experience from North American operators in inspecting for SCC and planar defects in ERW pipe that could be leveraged.	**Gap 2.5 (R):** There is a gap in developing a screening method for defects greater than the Level 2A ECA limits that will allow for targeted inspections. This is an outstanding gap. In addition, the gap closure plan identified in Level 1, Inspection (Gap 1.22) should be completed.
Repairs	As for Level 1	No gap.

Appendix 3: Level 2B

Theme	Guidance	Gaps and Closure Plan
Degradation and Defects		
Degradation	The impact of other degradation mechanisms, including interaction with H_2 embrittlement mechanisms, has to be considered separately and is out of scope of this document. **Commentary:** This Guideline only covers the impact of hydrogen on defects, i.e., the hydrogen embrittlement mechanism. Impact of other degradation mechanisms have to be assessed separately, and interaction with hydrogen must be considered. Level 2B is not suitable when interaction with other mechanisms is occurring.	For this situation, it is out of scope of this Guideline.
Planar Defects	No recommendation at present. **Commentary:** The appropriate defect size will depend on the basis of the S-N tests or a suitably derived correction factor to be used for defect free S-N curves.	**Gap 2.6 (R):** Determine appropriate planar defect size based on S-N tests or a suitable correction factor. Gap is open with no gap closure plan developed.
Body Planar Defects	No recommendation at present. **Commentary:** The appropriate defect size will depend on the basis of the S-N tests or a suitably derived correction factor to be used for defect free S-N curves.	As for Level 2B Planar Defects (Gap 2.6).
Volumetric Defects	As for Level 1	As for Level 1
Dents/Combinations	As for Level 1	As for Level 1
Wrinkling/buckling/local deformation/large strain events	As for Level 1	As for Level 1
Others	As for Level 1	As for Level 1
Material Requirements and Restrictions		
Hardness	As for Level 1	As for Level 1
Air Toughness (CVN)	As for Level 1	As for Level 1
H_2 Fracture Toughness	As for Level 2A	As for Level 2A
Ductility	As for Level 1	As for Level 1
Fatigue	Conduct bespoke S-N testing for geometry and environmental conditions under consideration. **Commentary:** It is possible to use S-N curve for H_2 directly on top	**Gap 2.7 (R):** Very limited S-N tests exist at present which potentially may be an

	of fatigue life from previous service as it is already standard practice to verify what has been consumed during service (using an accurate summary of loading history) and use a loading scenario for H_2 that is as accurate as possible.	issue for vintage pipelines. This is an outstanding gap that could be closed by an appropriate experimental programme.
Material Testing	As for Level 2A in addition S-N testing is subject to an outstanding gap.	**Gap 2.8 (R):** For S-N tests there is a gap on test protocols for S-N curve testing. This is an outstanding gap that could be closed by an appropriate experimental programme. The Materials testing gaps from Level 1 (Gap 1.10) and Level 2A (Gap 2.3) are also applicable here.
Grade	As for Level 2A	As for Level 2A
Yield Strength	As for Level 1	As for Level 1
UTS	As for Level 2A	As for Level 2A
Microstructure and chemical composition	As for Level 2A	As for Level 2A
Fracture arrest (running brittle fracture) - DWTT	As for Level 1	As for Level 1
Fracture arrest (running ductile fracture) - CVN	As for Level 1	As for Level 1
Residual stresses	As for Level 2A	As for Level 2A
Loading and Operations in H_2 service		
Loading	*Static loading:* As for Level 2A *Cyclic loading:* The limits based on an S-N approach are still an outstanding gap.	**Gap 2.9 (R):** There is a gap to establish the loading limits based on an S-N approach. This is an outstanding gap.
Design factors and derating factors, including location classes (onshore) and freespan / longitudinal stresses	As for Level 1	As for Level 1

and cyclic loading (offshore)		
Loading limitation due to static crack growth (da/dt)	As for Level 1	As for Level 1
Failure modes/limit states linked to environment e.g. onshore versus offshore	As for Level 1	As for Level 1
Operations e.g. pressure monitoring	As for Level 1	As for Level 1
Integrity Management	As for Level 1	As for Level 1
Gas Composition (H_2 limits and the use of inhibitor molecules)	As for Level 1	As for Level 1
Corrosion protection (internal and external coatings, clad layers, CP)	As for Level 1	As for Level 1
Inspection (Preparation for H_2 service and inspections once H_2 service has commenced)	As for Level 2A but replace "Level 2A ECA" with "Level 2B"	As for Level 2A
Repairs	As for Level 2A	As for Level 2A

Appendix 4: Level 3

Theme	**Guidance**	**Gaps and Closure Plan**
Degradation and Defects		
Degradation	The impact of other degradation mechanisms, including interaction with H_2 embrittlement mechanisms, has to be considered separately and is out of scope of this document. **Commentary:** This Guideline only covers the impact of hydrogen on defects, i.e., the hydrogen embrittlement mechanism. Impact of other degradation mechanisms have to be assessed separately, and interaction with hydrogen must be considered. Level 3 is not suitable when interaction with other mechanisms is occurring.	For this situation, it is out of scope of this Guideline.

Planar Defects	Full ECA should be executed for actual defects as per inspection findings subject to a gap on infield inspection tools that are suitably qualified for H_2 limits (See Level 1 Planar Defects).	Gap on qualifying and testing inspection tools is covered in Level 1 Planar Defects (Gap 1.2).
Body Planar Defects	Full ECA should be executed for actual defects as per inspection findings subject to the gap on infield inspection tools that should be suitably qualified (See Level 1 Planar Defects).	Gap on qualifying and testing inspection tools is covered in Level 1 Planar Defects (Gap 1.2).
Volumetric Defects	As for Level 1 or conduct Level 3 corrosion assessment as per API-579 Annex 2D using tensile data conducted in H_2 environment.	As for Level 1
Dents/Combinations	As for Level 1 or conduct Level 3 dent assessment as per API-579 determining the strain using Annex 2D with a fracture mechanics analysis as per Part 9 using H_2 affected material data.	As for Level 1
Wrinkling/buckling/local deformation/large strain events	As for Level 1 or conduct Level 3 dent assessment as per API-579 determining the strain using Annex 2D with a fracture mechanics analysis (if required) as per Part 9 using H_2 affected material data.	As for Level 1
Others	As for Level 1	As for Level 1
Material Requirements and Restrictions		
Hardness	As for Level 1	As for Level 1
Air Toughness (CVN)	As for Level 1	As for Level 1
H_2 Fracture Toughness	As for Level 2A	As for Level 2A
Ductility	As for Level 1	As for Level 1
Fatigue	As for Level 2A	As for Level 2A
Material Testing	As for Level 2A	As for Level 2A
Grade	As for Level 2A for X80 or below, otherwise bespoke material testing and assessments will have to be conducted to determine acceptability for grades higher than X80. **Commentary** Note that literature data for X100 does exist.	As for Level 2A
Yield Strength	As for Level 1 unless bespoke material testing and assessments are conducted.	As for Level 1
UTS	As for Level 2A	As for Level 2A
Microstructure and chemical composition	As for Level 2A	As for Level 2A
Fracture arrest (running brittle fracture) - DWTT	As for Level 1	As for Level 1
Fracture arrest (running ductile fracture) - CVN	As for Level 1	As for Level 1

Residual stresses	As for Level 2A	As for Level 2A
Loading and Operations in H_2 service		
Loading	The following are the cyclic pressure loading recommendations with the static loading recommendations detailed in Level 2A: *Onshore:* Pressure cyclic hoop loading: calculate number of cycles to failure based on B31.12 crack growth equation (if no bespoke testing is completed), times a suitable fatigue safety factor. Pressure cyclic axial loading: calculate number of cycles to failure times a suitable fatigue safety factor. Limited to half hoop stress *Offshore:* Pressure cyclic hoop loading: as for onshore Pressure and longitudinal axial cyclic loading: as for onshore + wave loading, VIV etc.	As for Level 2A
Design factors and derating factors, including location classes (onshore) and freespan / longitudinal stresses and cyclic loading (offshore)	As for Level 1	As for Level 1
Loading limitation due to static crack growth (da/dt)	As for Level 1	As for Level 1
Failure modes/limit states linked to environment e.g., onshore versus offshore	As for Level 1	As for Level 1
Operations e.g., pressure monitoring	As for Level 1	As for Level 1
Integrity Management	As for Level 1	As for Level 1
Gas Composition (H_2 limits and the use of inhibitor molecules)	As for Level 1	As for Level 1
Corrosion protection (internal and external coatings, clad layers, CP)	As for Level 1	As for Level 1
Inspection (Preparation for H_2 service and inspections once H_2 service has commenced)	As for Level 2A but replace "Level 2A ECA" with "Level 3"	As for Level 2A
Repairs	As for Level 2A	As for Level 2A

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