BEFORE THE PUBLIC UTILITIES COMMISSION
OF THE STATE OF CALIFORNIA

Order Instituting Rulemaking to Adopt Biomethane Standards and Requirements, Pipeline Open Access Rules, and Related Enforcement Provisions. U 39 G	R.13-02-008 (Filed February 13, 2013)

NOTICE OF FILING OF JOINT UTILITIES' HYDROGEN BLENDING COMPENDIUM REPORT

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Dated: February 14, 2025

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TO THE COMMISSION, ALL ATTORNEYS OF RECORD, AND INTERESTED PARTIES:

Please take notice that pursuant to Ordering Paragraph 10 of Decision ("D.") 22-12-057 of the California Public Utilities Commission and Executive Director's letter dated December 18, 2024, extending the deadline for filing from December 19, 2024, to February 14, 2025, Pacific Gas and Electric Company ("PG&E"), San Diego Gas & Electric Company, Southern California Gas Company, Southwest Gas Corporation (collectively, the "Joint Utilities") hereby submit the hydrogen blending compendium report ("Report").[1]

The Report consists of four attachments appended to this notice:

1. Letter of Transmittal – Prepared by the Joint Utilities;
2. Summary of Regulatory Proceedings – Prepared by the Joint Utilities;
3. Literature Review Chapter Summaries – Prepared by the Joint Utilities; and
4. Hydrogen Blending with Natural Gas Literature Review – Prepared by University of California, Riverside ("UCR").

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[1] Under Rule 1.8(d) of the Commission's Rules of Practice and Procedure, PG&E has been authorized to submit this notice on behalf of the Joint Utilities.

Respectfully submitted,

By: *_/s/ Nicholas D. Karkazis_*

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February 14, 2025

Letter of Transmittal –

Prepared by the Joint Utilities

February 14, 2025

California Public Utilities Commission

RE: R.13-02-008: Southern California Gas Company, San Diego Gas & Electric Company, Pacific Gas and Electric Company, and Southwest Gas Corporation's Hydrogen Blending Compendium Report

Dear Commission:

Pursuant to Ordering Paragraph (OP) 10 of Decision (D.) 22-12-057, enclosed please find Southern California Gas Company (SoCalGas), San Diego Gas & Electric (SDG&E), Pacific Gas and Electric (PG&E), and Southwest Gas Corporation's (Southwest Gas) (collectively, the Joint Utilities) Hydrogen Blending Compendium Report (the Compendium Report), summarizing the scope and relevant findings of existing relevant studies and regulatory proceedings that are complete and underway.

Purpose:

As prepared, the Compendium Report provides an independent and comprehensive review of hydrogen blending technical research published between July 2022 and August 2024. This report continues the work of the University of California, Riverside (UCR)'s Hydrogen Blending Impacts Study (Hydrogen Blending Study) sponsored by the California Public Utilities Commission (the Commission or CPUC), published in July 2022, and addresses the requirements of OP 10 of D.22-12-057. The review covers publicly available material, including peer-reviewed research articles, project reports, and other relevant documents.

The Joint Utilities sought an independent and impartial research organization to prepare the technical Literature Review portion of Compendium Report. The Joint Utilities selected UCR based on its expertise in the topic area, history with the proceeding, and authorship of the Hydrogen Blending Study. The costs related to UCR's fees are being tracked in the appropriate memorandum accounts as authorized by the CPUC.[1]

[1] *See* D.22-12-057; A.22-09-006 Administrative Law Judge's Ruling Denying Motion to Establish Balancing Accounts and Ordering Applicants to Establish Memorandum Accounts (October 28, 2024), at 4-5.

Background:

In D.22-12-057, the CPUC directed the Joint Utilities to file a Hydrogen Blending Compendium Report within two years from the issuance date of the decision, i.e., December 19, 2024, to identify existing relevant studies and regulatory proceedings that are complete and underway.[2] The Joint Utilities commissioned UCR to complete the independent review of technical studies based on the requirements under OP 10 of D.22-12-057.[3] The Joint Utilities directly reviewed related regulatory proceedings.

On March 1, 2024, in Application (A.) 22-09-006 the Joint Utilities submitted an Amended Application to establish live hydrogen blending demonstration projects by each utility (the Projects).[4] As detailed in the Amended Application, the five (5) proposed Projects will study hydrogen blending in controlled settings of the Joint Utilities' distribution and transmission systems. These demonstration projects aim to answer technical, operational, and safety questions that cannot be addressed by literature reviews or bench research alone.

Objective:

The objective of the Compendium Report is "to identify existing studies and regulatory proceedings that are complete and underway, and include findings related but not limited to:

(1) safety performance, safety thresholds, and integrity threat levels on various pipeline network components associated with hydrogen injection at various hydrogen blend percentages;

(2) leakage rates of the methane and hydrogen blend compared to pure methane;

(3) modeling to quantify lost hydrogen due to leakage;

(4) hydrogen permeation rates through polymer materials as compared to the natural gas permeation rates, and assessment of technologies for preventing or mitigating methane and hydrogen blend leakage in polymer and other pipeline materials;

(5) impact on storage fields, and modifications that may be necessary to maintain safety;

(6) analysis of the best equipment to monitor, detect, and control hydrogen leakage, and assessment of new hydrogen leak detection technologies;

(7) analysis of the impact of hydrogen dilution on heating value, and the required modifications of end-user equipment and appliances; and

(8) any and all human health issues identified."[5]

Additionally, as defined in Conclusion of Law 23 of D.22-12-057, "The purpose of the Hydrogen Blending Compendium Report is to summarize research that exists and consider issues that the parties

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[2] On December 18, 2024, the Executive Director granted the Joint Utilities' request for extension of time to file the Compendium Report by February 14, 2025.
[3] D.22-12-057 at 71.
[4] A.22-09-006, Joint Amended Application to Establish Hydrogen Blending Demonstration Projects.
[5] D.22-12-057, OP 10 at 71.

have highlighted in this proceeding or its successor proceeding. The Report should identify existing studies and regulatory proceedings that are complete or underway and summarize the scope and relevant findings of each.”[6] The Compendium Report evaluates existing studies and regulatory proceedings from July 2022 to August 2024.

Literature Review Context:

The Compendium Report presents a literature review of technical research results published within two years of the Hydrogen Blending Study. The review exclusively presents results from existing literature and does not address the practical feasibility or implications of blending hydrogen within California’s natural gas infrastructure or the proposed demonstration projects in A.22-09-006.

Some findings or topics discussed may not be directly applicable to the Joint Utilities’ demonstration Projects or the integration of hydrogen into California’s open access pipeline system. For example, the research on storage fields is beyond the scope of the proposed demonstration Projects which will be isolated from gas storage areas, in accordance with OP 7.b. in D.22-12-057. Additionally, the Literature Review acknowledges, "Laboratory experiments and numerical studies may not necessarily capture the broad range of real-world operating environments and conditions or consider all possible influencing factors."[7] To address this and support accessibility of findings for non-technical audiences, the Joint Utilities have prepared the Literature Review Chapter Summaries. The Joint Utilities’ summaries interpret and contextualize the findings from a pipeline operator perspective, addressing how the findings pertain to operating conditions in California’s natural gas pipeline system.

Attachments

1. Letter of Transmittal – Prepared by the Joint Utilities.
2. Summary of Regulatory Proceedings – Prepared by the Joint Utilities.
3. Literature Review Chapter Summaries – Prepared by the Joint Utilities.
4. Hydrogen Blending with Natural Gas Literature Review – Prepared by UCR.

[6] D.22-12-057 at 63.
[7] Hydrogen Blending Compendium Report, Executive Summary, Page 1.

Summary of Regulatory Proceedings -

Prepared by the Joint Utilities

Summary of Regulatory Proceedings

Summary

In Decision (D.) 22-12-057, the California Public Utilities Commission (Commission) directed Southern California Gas Company (SoCalGas), San Diego Gas & Electric Company (SDG&E), Pacific Gas and Electric Company (PG&E), and Southwest Gas Corporation (Southwest Gas) (collectively, the Joint Utilities) to file a Hydrogen Blending Compendium Report "to identify existing studies and regulatory proceedings that are complete and underway and include findings related but not limited to:

> (1) Safety performance, safety thresholds, and integrity threat levels on various pipeline network components associated with hydrogen injection, at various hydrogen blend percentages;
>
> (2) Leakage rates of the methane and hydrogen blend compared to pure methane;
>
> (3) Modeling to quantify lost hydrogen due to leakage;
>
> (4) Hydrogen permeation rates through polymer materials as compared to the natural gas permeation rates, and assessment of technologies for preventing or mitigating methane and hydrogen blend leakage in polymer and other pipeline materials;
>
> (5) Impact on storage fields, and modifications that may be necessary to maintain safety;
>
> (6) Analysis of the best equipment to monitor, detect, and control hydrogen leakage, and assessment of new hydrogen leak detection technologies;
>
> (7) Analysis of the impact of hydrogen dilution on heating value, and the required modifications of end-user equipment and appliances; and
>
> (8) Any and all human health issues identified."[1]

The Joint Utilities commissioned the University of California, Riverside (UCR) to complete the independent review of technical studies based on the requirements of OP 10, outlined above.

The Joint Utilities conducted a diligent search to identify utility proceedings in other jurisdictions in the United States and Canada that address the technical issues proposed

[1] D.22-12-057, Ordering Paragraph (OP) 10 at 71.

by OP 10. The Joint Utilities found that only the Commission specifically addresses findings related to these eight technical categories, via Rulemaking (R.)13-02-008 and Application (A.)22-09-006.

However, the Joint Utilities did find hydrogen blending demonstration projects and associated proceedings before other commissions, mainly related to seeking cost recovery for pilot and demonstration projects. These proceedings, included below, do not specifically address the technical issues proposed by OP 10 but are still valuable when examining the regulatory history of hydrogen blending. See Table 1, titled "Relevant Regulated Utility Hydrogen Blending Demonstration Projects, US and Canada," for utility hydrogen blending demonstration projects and their related regulatory proceedings.[2] Some of these projects and their findings to date are also described in the Hydrogen Blending Technical Report prepared by UCR. UCR's review shows a need for demonstration projects that can simulate the conditions and environment of California's natural gas infrastructure as knowledge gaps exist, especially under the real-world environments that systems operate under.

Table 1: Relevant Utility Hydrogen Blending Demonstration Projects, US and Canada

No.	Gas Utility	Location	Project	Sector	% Blend	Status as of 11/1/2024	Proceeding/ Docket
1	ATCO[3]	AB, CAN	Distribution demonstration	Distribution	5%	Operational	Proceeding 27256 (Alberta Utility Commission)
2	ATCO[4]	AB, CAN	Edmonton Convention Centre Hydrogen Blending	Distribution	20%	Completed	Proceeding 27256 (Alberta Utility Commission)
3	Calgary District Heating[5]	AB, CAN	Hydrogen Blending District Heating	Distribution	20%	In Progress	Proceeding 27256 (Alberta Utility Commission)
4	CenterPoint Energy[6]	MN, US	Renewable hydrogen distribution demo	Distribution	0.5% - 5%	Operational	Docket No. G-008/M-23-215 (Minnesota Public

[2] Table 1 includes projects with a regulatory proceeding and projects conducted by a regulated Investor-owned Utility where no proceeding or docket is available.
[3] ATCO. "Fort Saskatchewan Hydrogen Blending." July 1, 2020. https://gas.atco.com/en-ca/community/projects/fort-saskatchewan-hydrogen-blending-project.html.
[4] Government of Canada. "Hydrogen Strategy for Canada: Progress Report." May 2024. https://natural-resources.canada.ca/climate-change/canadas-green-future/the-hydrogen-strategy/hydrogen-strategy-for-canada-progress-report/25678#a7a.
[5] Calgary District Heating. "Hydrogen Blending Projects." https://calgarydistrictheating.com/hydrogen/.
[6] CenterPoint Energy. "Green hydrogen: accelerating a cleaner energy future." 2022. https://www.centerpointenergy.com/en-us/InYourCommunity/Documents/201229-02_Renewable%20Hydrogen.pdf.

No.	Gas Utility	Location	Project	Sector	% Blend	Status as of 11/1/2024	Proceeding/ Docket
							Utilities Commission)
5	Enbridge Gas Ohio (Dominion Energy Ohio)[7]	OH, US	Hydrogen Heights Pilot Program	Operations and Training Facility; Distribution	0.05	Launched pilot	23-0894-GA-AIR (Public Utilities Commission of Ohio)
6	Dominion Energy[8]	VA, US	Dominion Energy H2 Blending Pilot Projects	Distribution	up to 5%	Pilot Phase	Not Applicable (N/A)
7	Enbridge[9]	ON, CAN	Green hydrogen distribution demonstrati on	Distribution	2%	Operational	EB-2019-0294 (Ontario Energy Board)
8	Enbridge Energy (previously called Dominion Energy)[10]	UT, US	ThermH2 Project Phase 2 - Delta	Distribution	5%	Operational	N/A
9	Gazifère Inc[11]	QC, CAN	Gatineau Green Hydrogen Project	Distribution	Not Specifi ed	Not Specified	N/A
10	Hawai'i Gas[12]	HI, US	20% Blend	Production and Distribution	15%[13]	In operation & Planning	Docket No. 2024-0158 (Hawaii Public Utilities Commission)

[7] Dominion Energy. "Dominion Energy Ohio Starts Hydrogen Blending Pilot." https://news.dominionenergy.com/news?item=137989.

[8] Dominion Energy. "Dominion Energy advances hydrogen as next frontier of clean energy." April 19, 2021. https://news.dominionenergy.com/2021-04-19-Dominion-Energy-advances-hydrogen-as-next-frontier-of-clean-energy.

[9] Enbridge. "Low Carbon Energy Project – Hydrogen Blending at TOC." https://www.enbridgegas.com/about-enbridge-gas/projects/low-carbon-energy.

[10] Dominion Energy. "Dominion Energy Utah Starts Hydrogen Blending." April 3, 2023. https://news.dominionenergy.com/2023-04-03-Dominion-Energy-Utah-Starts-Hydrogen-Blending.

[11] Evolugen. "Evolugen and Gazifère Announce One of Canada's Largest Green Hydrogen Injection Projects to be Located in Quebec." February 25, 2021. https://evolugen.com/evolugen-and-gazifere-announce-one-of-canadas-largest-green-hydrogen-injection-projects-to-be-located-in-quebec/.

[12] Hawai'i Gas. "Hawaiʻi Gas Selects Eurus Energy America and Bana Pacific for Hydrogen and Renewable Natural Gas Projects." May 20, 2024. https://www.hawaiigas.com/posts/eurus-energy-america-and-bana-pacific-for-hydrogen-and-renewable-natural-gas-projects.

[13] Hawaiʻi Gas' synthetic natural gas (SNG), produced on Oʻahu since 1974, currently contains up to 15% hydrogen—the highest percentage of any natural gas utility in the United States. Through a future partnership with Eurus Energy America, Hawaiʻi Gas aims to increase the percentage of hydrogen in its fuel mix to up to 20%.

No.	Gas Utility	Location	Project	Sector	% Blend	Status as of 11/1/2024	Proceeding/ Docket
11	Liberty Utilities[14]	NB, CAN	MOU between Nu:ionic and Liberty Utilities	Production and Distribution	Not Specifi ed	Planning	Unknown
12	Liberty Utilities - New York Gas[15]	NY, US	Massena Blending Test	Production and Distribution	Not Specifi ed	Operational	N/A
13	National Grid[16]	NY, US	HyGrid	Distribution	5%	On hold	Case 23-G-0226 §9 (New York Public Service Commission)
14	New Jersey Natural Gas[17]	NJ, US	Green hydrogen distribution demonstrati on	Distribution	< 1 %	Operational	Docket GR21030679 (New Jersey Board of Public Utilities)
15	New Mexico Gas Company[18]	NM, US	Hydrogen Blending Demonstrati on: Phase 1 Onsite Blending, Phase 2: Distribution Demonstrati on	Distribution	5%	In Planning	No. 23-00255-UT (New Mexico Public Regulation Commission)
16	Columbia Gas of Pennsylvania[19]	PA, US	NiSource Hydrogen Blending Project	Distribution and end-use	2-10%	Pilot Phase	Docket No. R-2024-3046519 (Pennsylvania Public Utility Commission)

[14] Government of Canada. "Hydrogen Strategy for Canada: Progress Report." May 2024. https://natural-resources.canada.ca/climate-change/canadas-green-future/the-hydrogen-strategy/hydrogen-strategy-for-canada-progress-report/25678#a7a.
[15] Liberty. "Liberty Introduces First Hydrogen Pilot Program." June 11, 2024. https://libertyutilities.com/liberty-introduces-first-hydrogen-pilot-program-.html.
[16] National Grid. "One of the US' first green hydrogen blending projects launches on Long Island." December 15, 2021. https://www.nationalgrid.com/stories/journey-to-net-zero-stories/hygrid-green-hydrogen-blending-project-launches.
[17] S&P Global. "New Jersey Resources starts up 1st East Coast green hydrogen blending project." November 10, 2021. https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/new-jersey-resources-starts-up-1st-east-coast-green-hydrogen-blending-project-67570888.
[18] New Mexico Gas Company. "New Mexico Gas Company to Test Hydrogen Blending." December 3, 2021. https://www.nmgco.com/userfiles/files/12%203%2021%20Hydrogen%20Project.pdf.
[19] NiSource. "NiSource reaffirms commitment to a diverse energy future with launch of multi-phase hydrogen blending project." October 5, 2023. https://www.nisource.com/news/article/nisource-reaffirms-commitment-to-a-diverse-energy-future-with-launch-of-multi-phase-hydrogen-blending-project.

No.	Gas Utility	Location	Project	Sector	% Blend	Status as of 11/1/2024	Proceeding/ Docket
17	NW Natural[20]	OR, US	Methane Pyrolysis, Hydrogen Blending in Training Facility, Blending into Distribution	Operations and Training Facility; Distribution	0%	In Operation	Docket UG 490 (Oregon Public Utilities Commission)
18	Puget Sound Energy[21]	WA, US	PSE Hydrogen Blending Pilot Project	Operations and Training Facility; Distribution	Up to 15%	Pilot Phase	UE-240004 & UG-240005 (Washington Utilities and Transportation Commission)
19	Xcel Energy[22]	CO, US	Hydrogen-Natural Gas Blending Demonstrati on Project	Distribution and end use	Not specifie d	Planning	23A-0392EG (Colorado Public Utilities Commission)

In addition to projects in the United States and Canada, the Joint Utilities identified broader global interest in blending hydrogen into existing natural gas networks. Table 2, titled "Other Demonstration Projects," provides information on jurisdictions worldwide with known hydrogen blending demonstration projects or active hydrogen blending within existing gas networks. Regulatory proceedings and/or or docket numbers are not included/ available for these projects.

Table 2: Other Known Hydrogen Blending Demonstration Projects

No.	Company	Country	Project	Sector	% Blend	Status	Timeline
1	Aragon Hydrogen Foundation (FHA)[23]	Spain	HIGGS (hydrogen in gas grids) - FHA facilities	Transmission	20% & 100%	Operational	2020-2023

[20] NW Natural Holdings. "NW Natural and Modern Hydrogen Unveil Clean Hydrogen Production, Carbon Capture Project in Portland." May 16, 2024. https://ir.nwnaturalholdings.com/news/news-details/2024/NW-Natural-and-Modern-Hydrogen-Unveil-Clean-Hydrogen-Production-Carbon-Capture-Project-in-Portland/default.aspx.
[21] Puget Sound Energy. "Hydrogen Pilots." April 2021. https://www.pse.com/en/pages/Lower-Carbon-Fuels/Hydrogen-pilots.
[22] Xcel Energy. "Xcel Energy is envisioning a hydrogen-powered future" April 11, 2023. https://stories.xcelenergy.com/ArticlePage/?id=Xcel-Energy-is-envisioning-a-hydrogen-powered-future.
[23] Aragon Hydrogen Foundation. "HIGGS, a key project to promote decarbonisation in Europe coordinated by the Aragon Hydrogen Foundation." January 16, 2020. https://hidrogenoaragon.org/en/higgs-a-key-project-to-promote-decarbonisation-in-europe-coordinated-by-the-aragon-hydrogen-foundation/.

No.	Company	Country	Project	Sector	% Blend	Status	Timeline
2	ATCO[24]	Australia	Renewable hydrogen distribution demo	Distribution	10%	Planning	2022
3	Australian Gas Infrastructure Group[25]	Australia	Hydrogen Park South Australia (HyP SA)	Distribution	5%	Operational	2021
4	Australian Gas Infrastructure Group[26]	Australia	Hydrogen Park Gladstone	Distribution	10%	In Planning	2022
5	Australian Gas Infrastructure Group[27]	Australia	Hydrogen Park Murray Valley	Distribution	10%	Construction	Construction in 2023, Operational in 2025 --> 2030
6	Beijing Gas, SK E&S, Tsinghua University[28]	China	Beijing Green Hydrogen Demonstration	Production and distribution	Unknown	In planning	2022 to present
7	Cadent[29]	United Kingdom	HyDeploy - Keele	Distribution	20%	Complete	2019 to 2021
8	Cadent[30]	United Kingdom	HyDeploy - Winlaton	Distribution	20%	Operational	Aug 2021 to June 2022
9	CIIEG[31]	Colombia	Promigas H2Lab	Transmission and distribution	Various	Operational	2022 to present
10	CNPC, PetroChina, Sinopec[32]	China	PetroChina/CNPC	Transmission	Up to 24%	Pilot	2023 to present

[24] HyResource. "ATCO Hydrogen Blending Project." February 27, 2024. https://research.csiro.au/hyresource/atco-hydrogen-blending-project/.

[25] Australian Gas Infrastructure Group. "Hydrogen Park South Australia." https://www.agig.com.au/hydrogen-park-south-australia.

[26] Australian Gas Infrastructure Group. "Hydrogen Park Gladstone." https://www.agig.com.au/hydrogen-park-gladstone.

[27] Australian Government – Australian Renewable Energy Agency. "Hydrogen Park Murray Valley Facility." https://arena.gov.au/projects/hydrogen-park-murray-valley-facility/.

[28] Offshore Energy. "SK E&S and Beijing Gas to cooperate on LNG and hydrogen." May 27, 2022. https://www.offshore-energy.biz/sk-es-and-beijing-gas-to-cooperate-on-lng-and-hydrogen/.

[29] HyDeploy. "Live demonstration of blended hydrogen and natural gas started in Autumn 2019." https://hydeploy.co.uk/hydrogen/hydeploy-at-keele-live-pilot/.

[30] HyDeploy. "Hydrogen blending begins on the public gas network in Winlaton." August 13, 2021. https://hydeploy.co.uk/about/news/green-light-for-first-hydrogen-blending-on-a-public-gas-network/.

[31] CIIEG and Promigas. "Promigas H2Lab Green Hydrogen and Natural Gas blending project." November 2022. https://www.weltenergierat.de/wp-content/uploads/2023/11/H2_Colombia_Webinar_PROMIGAS.pdf.

[32] PV Magazine. "The Hydrogen Stream: Chinese companies push for hydrogen transport." April 18, 2023. https://www.pv-magazine.com/2023/04/18/the-hydrogen-stream-chinese-companies-push-for-hydrogen-transport/.

No.	Company	Country	Project	Sector	% Blend	Status	Timeline
11	Department of Science and Innovation, Bambili Energy[33]	South Africa	Hydrogen Valley South Africa	Distribution	Various (includes direct use)	In development	2021 to present
12	DNV, National Gas Transmission (NGT), OFGEM[34]	United Kingdom	FutureGrid	Transmission	Various (up to 100% tested)	Operational	2021 to present
13	E.ON, Avacon, DVGW[35]	Germany	H2-20 Hydrogen Blending Project	Distribution and end-use	Up to 20%	Operational	2021 to present
14	EDP, Galp, REN, ENGIE, Bondalti, McPhy, and others[36]	Portugal	GreenH2Atlantic	Production and distribution	Up to 5% initially	In development	2021 to present
15	Enagás, Acciona, CEMEX, IDEA, others[37]	Spain	Green Hysland	Production, distribution and end-use	Various (includes direct use)	Operational	2021 to present
16	Energinet[38]	Denmark	Hydrogen Maturation Project	Transmission	Up to 15%	Demonstratio n	2022 to present
17	ENGIE[39]	France	GRHYD - neighborhood and NGV refueling station (distribution)	Distribution	20%	Complete	2014 to 2019
18	EWE, GASCADE[40]	Germany	Hy2Infra	Transmission and distribution	Up to 100%	Operational	2024 -
19	FGSZ Ltd., MVM Group, University of Miskolc[41]	Hungary	GLUMEN Project	Transmission	Up to 10% proposed	Feasibility study	2023 to present
20	Firstgas Group, Hiringa Energy,	New Zealand	H2 Taranaki Roadmap	Distribution	Up to 20% by 2035	In planning	2025 (planned)

[33] Green Hydrogen Organization. "South Africa." https://gh2.org/countries/south-africa.
[34] DNV. "DNV to support UK National Gas Transmission with world first hydrogen pipeline research facility." https://www.dnv.com/news/dnv-to-support-uk-national-gas-transmission-with-world-first-hydrogen-pipeline-research-facility-250142/.
[35] H2 View. "Hydrogen blends being introduced into the German gas grid." November 1, 2021. https://www.h2-view.com/story/hydrogen-blends-being-introduced-into-the-german-gas-grid/.
[36] GreenH2Atlantic. "Renewable hydrogen, innovate for a better horizon." https://www.greenh2atlantic.com/.
[37] Green Hysland. "Deployment of a H2 Ecosystem on the Island of Mallorca." https://greenhysland.eu/.
[38] Energinet. "Research report: Hydrogen injected into the Gas Grid." https://en.energinet.dk/About-our-reports/Reports/Hydrogen-into-the-Gas-Grid/.
[39] ENGIE. "The GRHYD demonstration project." https://www.engie.com/en/businesses/gas/hydrogen/power-to-gas/the-grhyd-demonstration-project.
[40] EWE. "Green light from Brussels for the foundation of the European hydrogen infrastructure." February 15, 2024. https://www.ewe.com/en/media-center/press-releases/2024/02/green-light-from-brussels-for-the-foundation-of-the-european-hydrogen-infrastructure-ewe-ag.
[41] MFGT. https://mfgt.hu/en/Akvamarin.

No.	Company	Country	Project	Sector	% Blend	Status	Timeline
	Venture Taranaki, Others[42]						
21	Fluxys, Eoly, Parkwind[43]	Belgium	HYOFFWIND	Undefined	2%	Planning	First H2 by 2026
22	Gas Networks Ireland[44,45]	Ireland	HyTest (Phase 1), HyEnd (Phase 2)	Distribution	Up to 20%	In planning	2021 to present
23	GASCADE Gastransport GmbH[46]	Germany	HH2E	Transmission	Unknown	In Development	2018 to present
24	GasTerra[47]	Netherla nds	Hydrogen in natural gas on Ameland	Distribution and end use	up to 20%	Complete	2007 - 2011
25	Gasvalpo, Pietro Fiorentini[48]	Chile	Gasvalpo H2GN Project	Distribution	20%	Operational	2022
26	GNL Quintero, Acciona Energia, Enagas[49]	Chile	Green Hydrogen Quintero Bay	Distribution	Not Specified	In Development	Not Specified
27	GRTGaz[50]	France	Jupiter 1000	Distribution	6%	Operational	2018 to 2023
28	Jemena[51]	Australia	Western Sydney Green Gas Project	Distribution	2%	Operational	2021 to 2026

[42] Venture.org. “H2 TARANAKI ROADMAP.” https://www.venture.org.nz/assets/H2-Taranaki-Roadmap.pdf.
[43] Economie. “HYOFFWIND – Power to Gas.” September 2019. HYOFFWIND-Power-to-Gas-End-Report.pdf.
[44] Gas Networks Ireland. “Gas Networks Ireland publishes findings from its Hydrogen technical and safety feasibility study.” https://www.gasnetworks.ie/renewable/hydrogen/study/.
[45] Gas Networks Ireland. “Renewable Hydrogen and End-users’ Considerations for the Transition to a Renewable Gas Network (HyEnd).” November 2023. https://www.gasnetworks.ie/docs/renewable/HyEnd-Report.pdf.
[46] Hydrogen Europe. “HH2E agrees grid connection for German green H2 project.” January 12, 2024. https://hydrogeneurope.eu/hh2e-agrees-grid-connection-for-german-green-h2-project/.
[47]Voxeurope. “The possibility of a gas-free island.” https://voxeurop.eu/en/the-possibility-of-a-gas-free-island/#:~:text=On%20Ameland%2C%20off%20the%20coast%20of%20the,of%20hydrogen%20and%20natural%20gas%20in%20their.
[48] Pietro Fiorentini. “Inaugurated the first hydrogen blending station by Pietro Fiorentini.” January 10, 2023. https://www.fiorentini.com/en/news/inaugurated-the-first-hydrogen-blending-station-by-pietro-fiorentini/.
[49] GNLQuintero. “GNL Quintero, Acciona Energía and Enagás to implement joint green hydrogen project on Quintero Bay.” https://www.gnlquintero.com/en/2021/09/02/gnl-quintero-acciona-energia-and-enagas-to-implement-joint-green-hydrogen-project-on-quintero-bay/.
[50] GRTgaz. “Jupiter 1000.” February 20, 2020. https://www.grtgaz.com/medias/medias/communiques-de-presse/jupiter-1000.
[51] Jemena Gas Networks (NSW) Ltd. “Operational Compliance Report.” https://www.jemena.com.au/siteassets/asset-folder/documents/document-centre/gas/wshh/wsggp_operational-compliance-report_2024.pdf.

No.	Company	Country	Project	Sector	% Blend	Status	Timeline
29	Jemena, Solarig[52]	Australia		Distribution		Planning	MOU signed 2024
30	Netze BW (EBKG.DE)[53]	Germany	Hydrogen blends to home heating	Distribution	30%	Operational	2023
31	New Energy Coalition, Gasunie, Groningen Seaports, Others[54]	Netherla nds	HEAVENN (H2 Energy Applications in Valley Environments for Northern Netherlands)	Production, distribution and end use	Various (includes 100% hydrogen pipelines)	In development	2020 to present
32	Nortegas[55]	Spain	H2sArea	Distribution	10-20%	Complete	2021 to 2023
33	Petronas, Eneos Corporation[56]	Malaysia	Hydrogen-to-MCH	Distribution and end use	Up to 5% initially	In development	2022 to present
34	Portuguese Government, OMIP[57]	Portugal	Portugal H2 and Biomethane Blending Tender	Distribution	5-20%	Tender Open	2024 -
35	RAG Austria AG[58]	Spain	EUH2STARS	Storage	Pure H2 Storage	Planning	Through 2029
36	Scottish Gas Network (SGN)[59]	Scotland	The Aberdeen Vision	Transmission	2%	In Planning	2018-2028
37	Snam[60]	Italy	Pasta factory and a mineral water bottling company	Transmission	5 & 10%	Complete	2019 to 2020

[52] Renewables Now. "Jemena, Solarig to undertake green H2 blending project in Australia." May 29, 2024. https://renewablesnow.com/news/jemena-solarig-to-undertake-green-h2-blending-project-in-australia-859193/.
[53] Reuters. "Gas-hydrogen blending test for German home heating nears 30% target." February 13, 2023. https://www.reuters.com/business/energy/gas-hydrogen-blending-test-german-home-heating-nears-30-target-2023-02-13/.
[54] HEAVENN. "About HEAVENN." https://heavenn.org/about/.
[55] H2Sarea. "Developing advanced technological solutions for the safe distribution of hydrogen in the natural gas network." https://www.h2sarea.com/en/.
[56] JCorp. "JCorp and Sojitz Ink Collaboration on Decarbonisation Initiatives in Johor toward a Cleaner, Greener Energy Future for Industries." September 27, 2022. https://jcorp.com.my/wp-content/uploads/2023/08/Final-Press-Release_JLGxSojitz_MOU-on-Decarbonisation-Initiatives_240922_pdf.pdf.
[57] Hydrogen Insight. "Portugal opens first auction for hydrogen blending into the gas grid." May 30, 2024. https://www.hydrogeninsight.com/policy/portugal-opens-first-auction-for-hydrogen-blending-into-the-gas-grid/2-1-1651979.
[58] EU Stars H2. "EU Stars H2." https://www.euh2stars.eu/en/.
[59] Scottish Gas Network. "Aberdeen Vision Project." May 2020. https://www.sgn.co.uk/sites/default/files/media-entities/documents/2020-11/SGN-Aberdeen-Vision-Project_Final-Report_0520.pdf.
[60] SNAM. "Snam and hydrogen." https://www.snam.it/en/hydrogen_challenge/snam_hydrogen/.

No.	Company	Country	Project	Sector	% Blend	Status	Timeline
			(transmission demo)				
38	ThueGA Group, Energie Suedbayern, Energienetze Bayern, H2Go Power[61]	Germany	H2Direkt	Distribution	Up to 100%	Pilot Project Completed, in development	2021 to present
39	Uniper, Siemens, Linde[62]	Germany	GreenHydro Chem Central Germany	Distribution	Unknown	In planning	2019 to present

Existing Codes and Standards for Hydrogen and Hydrogen Blending

Hydrogen gas, and in some cases blended hydrogen gas, follows its own set of codes and standards that consider the thermochemical properties of hydrogen. These codes and standards are managed by various non-governmental, non-profit organizations, including the American National Standards Institute (ANSI), the American Society of Mechanical Engineers (ASME), the CSA Group (CSA), the Compressed Gas Association (CGA), the National Fire Protection Association (NFPA), the International Code Council (ICC), and the International Standards Organization (ISO). In addition, gas utilities have established natural gas and biomethane standards that address the specific needs of their respective territory and system.

Many of the codes and standards for handling pure hydrogen can be applied to hydrogen production required to carry out the Joint Utilities' proposed hydrogen blending demonstration projects (the Projects). For example, codes focused on handling pure hydrogen will dictate and guide many aspects related to hydrogen production and storage for the proposed Joint Utilities' Projects, including equipment siting, safe distances, onsite hydrogen storage, and hydrogen production.

The public can access a comprehensive list of hydrogen Codes and Standards via the Hydrogen Tools Portal.[63] This tool was developed by the Pacific Northwest National Laboratory, through support from the United States (US.) Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy (EERE). Additionally, the tool provides a

[61] Thuega. "H2Direkt: 100 Prozent Wasserstoff im Bestandsnetz wird konkret." August 8, 2023. https://www.thuega.de/pressemitteilungen/h2direkt-100-prozent-wasserstoff-im-bestandsnetz-wird-konkret/.
[62] Uniper. "Siemens and Uniper join forces to decarbonize power generation." April 8, 2020. https://www.uniper.energy/news/siemens-and-uniper-join-forces-to-decarbonize-power-generation/.
[63] Hydrogen Tools. "Fuel Cell Codes and Standards." https://h2tools.org/fuel-cell-codes-and-standards.

user access to a Hydrogen Safety Bibliographic Database (Database) that includes reports, articles, books, and other resources on hydrogen safety related to production, storage, distribution, and use. The Database includes references related to OP 10, covering topics such as hydrogen properties and behavior, safe operating and handling procedures, leaks, dispersion, flammable vapor cloud formation, embrittlement, and other effects on material properties, sensors, tracers, and leak detection technologies.[64]

Federal Efforts Related to Hydrogen Blending

The U.S. government also is attempting to address technical barriers to blending hydrogen in natural gas pipelines. For example, DOE's HyBlend initiative is one example of the research being conducted to address technical barriers to blending hydrogen in natural gas pipelines.[65] This work is part of DOE's Hydrogen Program, led by the Hydrogen and Fuel Cell Technologies Office within the EERE.[66] The following list identifies several federal initiatives as of January 2025 related to hydrogen blending:

1. Pipeline and Hazardous Materials Safety Administration (PHMSA): PHMSA has several initiatives and working groups dedicated to hydrogen pipeline safety. They focus on developing and validating leak detection sensors, assessing integrity threats, and advancing safety regulations for hydrogen transportation. Some of the topics include:
    - Advancing Hydrogen Leak Detection and Quantification Technologies Compatible with Hydrogen Blends[67]
    - Expanding Hydrogen Storage to Porous Rock Formations: A Framework for Estimating Feasibility & Operational Considerations[68]
    - Establishing the Technical Basis for Enabling Safe and Reliable Underground Hydrogen Storage Operations[69]

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[64] H2 Hydrogen Tools. "H2Tools Bibliography." https://h2tools.org/bibliography.
[65] U.S. Department of Energy. "HyBlend: Opportunities for Hydrogen Blending in Natural Gas Pipelines." https://www.energy.gov/eere/fuelcells/hyblend-opportunities-hydrogen-blending-natural-gas-pipelines.
[66] Energy.gov. "Hydrogen Program." https://www.hydrogen.energy.gov/.
[67] PHMSA. "Advancing Hydrogen Leak Detection and Quantification Technologies Compatible with Hydrogen Blends." https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=979.
[68] PHMSA. "Expanding Hydrogen Storage to Porous Rock Formations: A Framework for Estimating Feasibility & Operational Considerations." https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=984.
[69] PHMSA. "Establishing the Technical Basis for Enabling Safe and Reliable Underground Hydrogen Storage Operations." https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=999.

2. DOE HyBlend Initiative: The HyBlend initiative addresses technical barriers to blending hydrogen in natural gas pipelines. Key aspects of HyBlend include materials compatibility research and development (R&D), techno-economic analysis, and life cycle analysis that will inform the development of publicly accessible tools that characterize the opportunities, costs, and risks of blending. [70]
3. DOE Subsurface Hydrogen Assessment, Storage, and Technology Acceleration (SHASTA): National Energy Technology (NETL), Pacific Northwest National Laboratory (PNNL), and Lawrence Livermore National Laboratory (LLNL) are assessing the viability, safety, and reliability of storing hydrogen or hydrogen-natural gas blends in subsurface environments. The project aims to determine technical feasibility, mitigate risks, and develop technologies for large-scale hydrogen storage, leveraging existing natural gas infrastructure.[71]
4. DOE Hydrogen and Fuel Cell Technologies Office (HFTO): The Hydrogen and Fuel Cell Technologies Office (HFTO) focuses on research, development, and demonstration of hydrogen and fuel cell technologies across multiple sectors, enabling innovation, a strong domestic economy, and a clean, equitable energy future. [72]
5. DOE Hydrogen Interagency Task Force (HIT): A working group dedicated to end-use applications of hydrogen aims to develop strategies for its safe and efficient use in various sectors, including transportation, industry, and power generation.[73]
6. DOE- ARPA-E: Support the development of innovative approaches for hydrogen gas detection and quantification across the hydrogen supply chain. Cost-effective, accurate measurements of hydrogen gas will facilitate detection for discovery and mitigation of emissions to maximize the climate and economic benefits of hydrogen production. [74]

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[70] HyBlend. "HyBlend: Opportunities for Hydrogen Blending in Natural Gas Pipelines." https://www.energy.gov/eere/fuelcells/hyblend-opportunities-hydrogen-blending-natural-gas-pipelines.
[71] SHASTA. "Subsurface Hydrogen Assessment, Storage, and Technology Acceleration." https://netl.doe.gov/sites/default/files/rdfactsheet/R-D232%20-%20SHASTA.pdf .
[72] U.S. Department of Energy. "Hydrogen and Fuel Cell Technologies Office." https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office.
[73] Energy.Gov. "Hydrogen Interagency Task Force." https://www.hydrogen.energy.gov/interagency.
[74] ARPAE. H2SENSE. https://arpa-e.energy.gov/technologies/exploratory-topics/H2SENSE.

7. DOE Sponsored Research and Development: Development of modeling tools through the collaboration of the Department of Energy with national labs and other entities. For example:
    - Hydrogen modeling for permeability by Savannah River National Laboratory[75]
    - NFPA 497 for Standoff Distance Calculation with the use of HyRam [76]

In addition, the federal Infrastructure Investment and Jobs Act (IIJA) passed in 2021 established clean hydrogen initiatives to accelerate the use of clean hydrogen. The Clean Hydrogen Research and Development Program will advance and support "the safe and efficient delivery of hydrogen or hydrogen-carrier fuels...including retrofitting the existing natural gas transportation infrastructure system to enable a transition to transport and deliver increasing levels of clean hydrogen, clean hydrogen blends, or clean hydrogen carriers."[77] Further, the IIJA directed the development of the National Clean Hydrogen Strategy and Roadmap, including "identifying opportunities to use, and barriers to using, existing infrastructure, including all components of the natural gas infrastructure system...for clean hydrogen deployment."[78]

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[75] M. Kane. "Permeability, Solubility, and Interaction of Hydrogen in Polymers- An Assessment of Materials for Hydrogen Transport." https://digital.library.unt.edu/ark:/67531/metadc902701/m2/1/high_res_d/927901.pdf.

[76] Sandia National Laboratories. "Modeling and Risk Assessment of Hydrogen/Natural Gas Blends." https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review24/scs035_glover_2024_p.pdf?sfvrsn=a478877f_3.

[77] 42 USC § 16154(e)(6)(A).

[78] 42 USC § 16161b(a)(2)(E).

IOU Chapter Summaries

Chapter-By-Chapter Summary of Hydrogen Blending Literature Review

Purpose of Summary

The following is a chapter-by-chapter summary of the Hydrogen Blending with Natural Gas Literature Review (Literature Review) prepared by UC Riverside. The summary is designed to enable non-technical readers and the general public to understand and contextualize the research surveyed in the Literature Review as it relates to the California natural gas system. This summary and interpretation of the Literature Review findings was prepared by Southern California Gas Company (SoCalGas), San Diego Gas & Electric Company (SDG&E), Pacific Gas and Electric Company (PG&E), and Southwest Gas Corporation (Southwest Gas) (collectively, the Joint Utilities). This summary may be used as a reference when reading the Literature Review, or as a stand-alone document.

Chapter 1- Impact on materials, pipeline network components and associated safety and performance thresholds[1]

This chapter reviews recent findings on the impacts of hydrogen-natural gas blends on common pipeline materials and other network components used in the natural gas infrastructure.

Chapter 1 Key Take Aways

There are various studies and demonstration projects analyzing the impacts on pipeline components and performance. Research suggests that traditional natural gas pipeline materials can be utilized with hydrogen blends, particularly up to 20% hydrogen by volume. However, additional considerations and research are needed to evaluate hydrogen blends in steel pipeline materials, specifically at higher pressures and stress levels, such as those seen in California's natural gas transmission systems. The impact to gas compression and transport needs to be evaluated on a case-by-case basis as any subsection of pipeline can vary in capacity.

Real-world demonstrations reviewed build on a growing body of research indicating that the impacts of blended hydrogen to materials, safety thresholds, and performance can be managed and mitigated when operating a natural gas pipeline system. Therefore, specific demonstration projects are needed to verify these results for materials, performance, and operating conditions seen in California.

Impacts on Pipeline Materials

Pipeline Materials Background

The California natural gas pipeline system is generally composed of two main classes of materials: metals and plastics. The system is segmented into two subsystems: transmission and distribution. The transmission system has higher operating pressures and typically uses metal (steel) pipeline materials. The distribution system generally has lower operating pressures and is typically composed of a combination of steel and plastic pipeline materials. Materials used on the distribution system vary

[1] For ease of reference, the chapter titles match those of the Literature Review.

depending on operating pressure, pipeline stress, and vintage (the year in which the pipe was installed). While both steel and plastic pipelines exist in the distribution system, the most commonly installed pipelines today are plastic.[2] In addition to pipelines, natural gas infrastructure contains parts such as gaskets and seals that are used on the system to create a tight seal between connecting pipe sections, preventing leaks of natural gas at joints and flanges. The Literature Review considers the impacts of hydrogen blends on different pipeline materials, as well as on gaskets and seals.

The following defined terms and concepts may be helpful when reviewing Chapter 1:

- **Cyclic Loading:** the repeated application of stress, strain, or stress intensity to a material or component[3]
- **Ductility**: the ability of a material to have its shape changed without losing strength or breaking[4].
- **Embrittlement**: the loss of a material's ductility, due to a chemical or physical change, leading to crack propagation without appreciable deformation (permanent change).[5] In other words, a reduction in ductility or the phenomenon of a material becoming more brittle
- **Fatigue Crack Growth**: the propagation or advancement of cracks in a material subjected to cyclic loading. When a material is repeatedly loaded and unloaded (under stress or stain), cracks can initiate and grow progressively under repeated stress or strain.[6]
- **Fracture Resistance**: a material's ability to withstand stress without breaking. Also known as Fracture Strength, refers to the ability of a material to resist failure under different types of applied loading, such as tensile, compressive, or bending forces. It is dependent on the surface quality of the material, with imperfections like grooves and scratches reducing the fracture strength.[7]
- **Fracture Toughness**: A material's ability to resist crack propagation under applied stress.[8]
- **Integrity Management/Pipeline Integrity Management**: a set of safety management, operations, maintenance, evaluation, and assessment processes that are implemented in an integrated and rigorous manner[9]

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[2] Pipeline and Hazardous Materials Safety Administration. "Gas Distribution, Gas Gathering, Gas Transmission, Hazardous Liquids, Liquefied Natural Gas (LNG), and Underground Natural Gas Storage (UNGS) Annual Report Data." Available at https://www.phmsa.dot.gov/data-and-statistics/pipeline/gas-distribution-gas-gathering-gas-transmission-hazardous-liquids.

[3] Springer Nature Link. "Cyclic Loading and Cyclic Stress." Available at https://link.springer.com/referenceworkentry/10.1007/978-0-387-92897-5_244#:~:text=Definition,referred%20to%20as%20fatigue%20degradation.

[4] Merriam-Webster. "Ductility." January 8, 2025. Available at https://www.merriam-webster.com/dictionary/ductility.

[5] ScienceDirect. "Embrittlement." Available at https://www.sciencedirect.com/topics/engineering/embrittlement#:~:text=Embrittlement%20is%20the%20loss%20of,propagation%20without%20appreciable%20plastic%20deformation.

[6] ScienceDirect. "Fatigue Crack Growth." Available at https://www.sciencedirect.com/topics/materials-science/fatigue-crack-growth.

[7] ScienceDirect. "Fracture Strength." Available at https://www.sciencedirect.com/topics/chemistry/fracture-strength.

[8] ScienceDirect. "Fracture Toughness." Available at https://www.sciencedirect.com/topics/chemistry/fracture-toughness#:~:text=%E2%80%9CFracture%20toughness%E2%80%9D%20describes%20the%20resistance,fracture%20toughness%20of%20the%20material.

[9] U.S. Department of Transportation. "Overview : Integrity Management." Available at https://primis.phmsa.dot.gov/comm/Im.htm#:~:text=Both%20the%20hazardous%20liquid%20and,provide%20enhanced%20protection%20for%20HCAs.

- **Methane**: A chemical compound with one carbon atom and four hydrogen atoms (CH_4) that is gaseous at standard temperature and pressure.[10]
- **Natural Gas**: Natural gas is a fossil fuel energy source that contains many different compounds; the largest component of natural gas is methane. [11]
- **Partial Pressure**: refers to the pressure exerted by a gas alone (in this case hydrogen) in a mixture of gases, essentially representing its contribution to the total pressure of the mixture.[12] For example, a 10% hydrogen blend by volume will have a partial pressure of 6 pounds per square inch gauge (psig) in a 60 psig pipeline and a partial pressure of 20 psig in a 200 psig pipeline.
- **Peak Load**: The maximum load a material specimen can withstand before failure[13]
- **Operating Pressure:** the amount of internal force applied to the walls of some type of pressure vessel, like a pipeline, during normal conditions[14]
- **Specified Minimum Yield Strength (SMYS)**: a parameter that provides the amount of stress applied to a steel pipe before it begins to deform permanently.[15]
- **Specified Minimum Yield Strength (SMYS) Percentage**: Indicates the maximum allowable stress level a pipe can experience before permanent deformation, expressed as a percentage of its specified minimum yield strength. The percentage of SMYS is used to determine a pipeline's maximum allowable operating pressure.
- **Strain**: measurement of how much an object deforms relative to its original length when subjected to an external force.[16]
- **Stress**: the force applied to an object divided by the cross-sectional area of that object.[17] There are various stress types related to pipelines, including hoop stress, axial stress, bending stress, torsional stress, and fatigue stress.

Impact on Steel Pipelines

While there is consensus in the Literature Review that hydrogen can affect fatigue crack growth rate, fracture resistance, and ductility in steel pipelines, these impacts do not preclude blending of hydrogen into steel pipeline materials (Literature Review Reference (UCR) 3, 4, 5, 6). [18] These parameters are often used to evaluate performance and integrity of steel pipelines. Generally, fatigue crack growth increases with increasing hydrogen concentration, and it is more pronounced at higher stress (UCR 3). The impacts

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[10] US Energy Information Administration. "Natural Gas Explained." Available at https://www.eia.gov/energyexplained/natural-gas/.
[11] Ibid
[12] Khan Academy. "Dalton's law of partial pressure." Available at https://www.khanacademy.org/science/chemistry/gases-and-kinetic-molecular-theory/ideal-gas-laws/a/daltons-law-of-partial-pressure#:~:text=The%20contribution%20of%20hydrogen%20gas,attractive%20forces%20between%20the%20gases.
[13] UCR Literature Review, p.13.
[14] Corrosionpedia. "Operating Pressure." Available at https://www.corrosionpedia.com/definition/835/operating-pressure.
[15] ScienceDirect. "Specified Minimum Yield Strength." Available at https://www.sciencedirect.com/topics/engineering/specified-minimum-yield-strength.
[16] Boston University. "Mechanics of Materials: Strain." Available at https://www.bu.edu/moss/mechanics-of-materials-strain/#:~:text=Deformation%20is%20a%20measure%20of,by%20the%20Greek%20letter%20gamma.
[17] Boston University. "Mechanics of Materials: Stress." Available at https://www.bu.edu/moss/mechanics-of-materials-stress/.
[18] Citations to "UCR" refer to UCR Report's reference numbers cited therein.

of blended hydrogen are generally observed to be related to the SMYS percentage. This ratio is the maximum allowable operating pressure of the pipeline compared to the rated SMYS of the pipeline. To reduce effects of hydrogen on steel microstructure, surface treatments or coatings/liners can also be explored as mitigation strategies (UCR 17-20). When evaluating hydrogen blends, it is also important to consider the partial pressure of the hydrogen, as this characterizes the pressure that the hydrogen gas alone applies to the pipeline.

Distribution System Impacts
The distribution system is defined as pipelines operating at 20% SMYS or less.[19] While the distribution system can operate at a variety of pressure ranges, most of the distribution system operates at less than 60 psig. There are portions of the distribution system that may operate at higher pressures, which is normally separated by limiting or regulator stations. Literature suggests that fatigue crack growth rate can be accelerated at small partial pressures of hydrogen such as 1 bar (14.5 psi); however, it generally increases with increasing hydrogen concentration, and it is more pronounced at higher stress levels (UCR 3). From an integrity management perspective, 20% blended hydrogen or less in a steel distribution pipe poses less risk than it would through a steel transmission pipe due to the lower partial pressure of hydrogen and lower SMYS percentage of the distribution system.

Transmission System Impacts
Steel transmission pipelines operate at higher pressures and higher SMYS percentages than distribution pipelines. Therefore, under the same volumetric hydrogen blending concentrations, this can result in greater pipeline stress due to higher partial pressures. The introduction of hydrogen can impact fatigue crack growth rates; however, the literature suggests that the cycling loading (or cyclic pressure) is what further drives the fatigue crack growth rate (UCR 12). For example, one study indicated accelerated fatigue crack growth at a hydrogen partial pressure of 21 MPA (3,046 psig) (UCR 3). In this scenario, the partial pressure of the hydrogen alone exceeds the operating pressure of most transmission pipeline systems. Exposure to blended hydrogen for steel pipes can result in reduced fracture toughness and ductility (UCR 8, 21, 25). Various steel pipe surface treatments have been studied for their effects on reducing hydrogen embrittlement in steel pipelines and this is an ongoing area of research (15, 16, 17, 18, 19, 20). Further research is also required to understand blended hydrogen's impact on steel pipe welding and inherent defects (UCR 27, 30, 34, 35, 36). Future demonstrations can seek to address some of these gaps.

Impact on Plastic Pipelines

Literature reviewed by UCR indicate no significant impacts from hydrogen natural gas blends on plastic ("polymeric") materials at pressure conditions observed on the California gas distribution system (UCR 3, 55, 56). The most common plastic pipeline used in California's natural gas distribution system is polyethylene (UCR 6). The impact of hydrogen on medium density and high-density polyethylene were both examined and showed no noticeable effects or meaningful impacts (UCR 55, 56). Even under high pressures noted in literature, which may exceed those of typical operating pressures in the distribution system, results show no effect on plastic pipeline fatigue life and fracture resistance, while tensile strength is only somewhat reduced (UCR 3, 55, 56). The literature further suggests that the relatively small reduction of yield strength and the strain at the first peak load[20] may be the result of exposure to high pressure rather than the gas present (UCR 55). These properties are generally what are used to best

[19] U.S. Department of Transportation. Pipeline and Hazardous Materials Safety Administration. "Interpretation Response #PI-16-0015." Available at https://www.phmsa.dot.gov/regulations/title49/interp/pi-16-0015.
[20] The maximum load a material specimen can withstand before failure.

understand the integrity of plastic pipelines. Research on plastic pipeline material suggests promise for incorporating hydrogen blends with their existing use case, especially up to the 20% threshold.

Impact on Gaskets and Seals

Materials used in gaskets and seals predominantly include elastomers and semicrystalline thermoplastics, generally referred to as "elastomer materials." Elastomer materials did not show signs of reduced permeability, hardness, or ductility when exposed to hydrogen at normal gas system operating pressures, with the exception of FKM samples showing minor reduction in ductility (UCR 58).   In one laboratory study, elastomer materials were exposed to very high pressure conditions, up to ten times higher than the typical operating pressures of transmission pipelines (UCR 57). Under these artificial operating conditions, some swelling was observed (UCR 57).   Thus, research on gaskets and seals suggests that most materials reviewed in the literature can be suitable for use with hydrogen blends under typical transmission and distribution pipeline operating conditions.

Impacts on Meters, Pressure Regulators, and Valves

It is important to consider material compatibility with valves, pressure regulators, and meters when introducing hydrogen blends to gas system infrastructure. Valves and pressure regulators are typically constructed of steel and may have components made of polymer materials. The impacts to these materials are discussed above. Research also examined the accuracy of gas meters with hydrogen blends.

Metering is how utilities measure and bill for delivered energy. Some meters, such as turbine, rotary, and thermal mass meters, are susceptible to slight measurement errors when used with hydrogen blends, but most lab tests show the measurements are within the allowable error range (UCR 64). Measurement errors can be addressed using a correction factor, a common practice in the natural gas industry today (UCR 3). Diaphragm meters are the most commonly deployed meter types in the California natural gas system. Other meter types such as rotary, turbine, ultrasonic, and thermal mass meters may be used to monitor larger gas flows such as for large commercial or industrial customers. With respect to the durability of natural gas meters with hydrogen, one study observed no impact on materials of diaphragm, ultrasonic, and turbine gas meters with up to 30% hydrogen blended in natural gas (UCR 64, 67).

Impact on Gas Compression and Transport

Demonstrations on real-world infrastructure, such as those performed by ATCO in Canada (discussed below), have shown that blending on the distribution system does not necessarily require increased gas compression, as pipeline segments may be able to accommodate an increase in flow rate without the need for additional compression. Compression is used by pipeline operators to increase the pressure within a pipeline, which can be used to increase the flow rate and amount of energy delivered by that pipeline. Hydrogen gas has approximately one-third the energy content of typical natural gas on a volumetric basis.[21] Numerical modeling suggests that if gas pipeline pressure conditions are kept constant for methane blends containing 10% hydrogen, the gas flow rate increases by 4% (UCR 71). With a 20% hydrogen blend the flow rate would increase by 9% (UCR 71). Modeling also suggests that to maintain the same energy transmission capacity with hydrogen-natural gas mixtures, operating pressures need to be increased to achieve higher gas flow rates (UCR 72, 73, 74).

[21] Literature Review, p. 23.

The live blending demonstration projects reviewed in the literature did not report any needs for increased compression, equipment changes, or operational modifications. While operational parameters of the pipeline system should certainly be considered, each subsection of pipeline varies in capacity and operational characteristics. And thus, operational requirements to deliver sufficient energy to consumers would need to be evaluated on a system-by-system basis. Further research is needed to understand gas compression needs for the California system and in which sections of the network.

Hydrogen Blending Pilots and Demonstrations

Several live hydrogen-blending demonstration projects were evaluated in the literature review that used common pipeline network components and successfully operated their systems with up to 20% hydrogen blends.

Distribution System Demonstrations

ATCO Gas and pipelines has performed two separate demonstrations of hydrogen blending in both Australia and Canada, blending 2% and 5% into their existing infrastructure, respectively (UCR 85, 86,87). No infrastructure malfunctions were reported, and the utility intends to increase blending to 10% (Australia) and 20% (Canada). Enbridge Gas Inc. currently serves approximately 3,600 residential customers with a 2% hydrogen blended natural gas using the distribution network located in Markham, Ontario (UCR 88). In France, GRT Gaz's Jupiter 100 project successfully blended up to 2% hydrogen by volume into the existing natural gas system, serving industrial end uses (UCR 81). The H2-20 pilot project evaluated by the German Association for Gas and Water successfully demonstrated hydrogen blends of 10%, 15%, and 20% into distribution natural gas network that delivered gas to about 350 domestic and commercial customers (UCR 82). Cadent's HyDeploy 2 project demonstrated the blending of 20% hydrogen in a small portion of the natural gas distribution system in Winlaton, England with no reported impacts to plastic materials, steel materials, or leakage (UCR 83). Australian Gas Infrastructure Group's Hydrogen Park South Australia project in Adelaide, Australia blended up to 5% hydrogen into an existing gas distribution network, with no impact to blended gas composition downstream of injection and no gas leaks found, demonstrating the successful operation of the existing pipeline materials and components (UCR 84).

Transmission System Demonstrations

The FutureGrid Demo Project in the UK, performed by DNV, National Gas Transmission, and OFGEM, focused on various hydrogen blend percentages in addition to 100% hydrogen on the transmission system.[22] This project tested various concentrations of blended hydrogen (0~100%) on X52, X60, and X70 steels, following the ASME B31.12 standard. The results showed that these materials are qualified for use with 100% hydrogen at pressures up to 106.5 bar (1545 psig) (UCR 54).

Chapter 2 – Leakage rate of hydrogen blends

This chapter reviews studies comparing the leak rates and dispersion characteristics of hydrogen/ hydrogen-methane/hydrogen-natural gas blends to pure methane or natural gas.

The following defined terms and concepts may be helpful when reviewing Chapter 2:

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[22] DNV. "DNV to support UK National Gas Transmission with world first hydrogen pipeline research facility." December 14, 2023. https://www.dnv.com/news/dnv-to-support-uk-national-gas-transmission-with-world-first-hydrogen-pipeline-research-facility-250142/.

- **Dispersion:** The process where a leaked or released gas (natural gas or blended gas) cloud gradually spreads out and mixes with the surrounding air due to factors like wind, temperature differences, and atmospheric conditions.
- **Jet Flame/Jet Fire:** A flame type resulting from the discharge of liquid, vapor, or gas into free space from an orifice, the momentum of which induces the surrounding atmosphere to mix with the discharged material.[23] These terms are used interchangeably in the Literature Review.
- **Leak:** An unintended release of gas from a contained environment like a pipeline, appliance, or connection, through an opening (such as a hole or crack), where the gas escapes into an area it shouldn't be. Note: If contained gas moves through the wall of a material, that is permeation and typically not identified as a leak.[24] Permeation is discussed in Chapter 3.
- **Lower Flammability Limit (LFL):** The lowest concentration of a flammable gas or vapor in air that can ignite when an ignition source is present.[25]
- **Mass Flow Rate:** The mass of fluid (gas) which passes through per unit time. [26]
- **Volumetric Flow Rate:** The volume of fluid (gas) that passes through per unit time.[27]

Chapter 2 Key Takeaways

The data from both experimental and demonstration projects shows no observed increase in leaks due to the introduction of hydrogen blends ranging from 0-20% in natural gas pipeline systems. In addition, research infers that should an existing natural gas pipeline leak be repaired to be leak-tight, it would also be leak-tight for hydrogen blends. Additional data from demonstration projects can help solidify these observations and provide additional data points for distribution and transmission pipelines for long term real-word operating conditions. A discussion of leakage measurement technology is included in Chapter 6.

Comparison of leak rates of hydrogen and hydrogen blends to pure methane or natural gas

Hydrogen in its pure form (100%) behaves differently from hydrogen blended with natural gas. For example, pure hydrogen and blended hydrogen demonstrate unique gas properties such as density and viscosity. This could lead to different gas behavior for leakage, dispersion, and other properties. Several demonstration projects showed that compared to natural gas, hydrogen-methane blends up to 20% hydrogen do not show an increase in leakage for commonly used materials in the California gas system (UCR 60,83,84,100).

Research infers that if any leaks on natural gas system (appliance, valves, connection, etc.) are repaired for natural gas to be leak tight, the system should also be leak tight for hydrogen blends. For example, at

[23] Center for Chemical Process Safety. "Jet Fire." Available at https://www.aiche.org/ccps/resources/glossary/process-safety-glossary/jet-fire.

[24] Energy Robotics. "Gas Leaks – Definition, Types, and Detection." October 2, 2024. Available at https://www.energy-robotics.com/post/gas-leak-detection.

[25] ScienceDirect. "Evaluation of lower flammability limits of fuel-air-diluent mixtures using calculated adiabatic flame temperatures." March 2006. Available at https://www.sciencedirect.com/science/article/abs/pii/S0304389405004218#:~:text=The%20lower%20flammable%20limit%20(LFL,the%20SuperChems%20software%20%5B4%5D.

[26] Bronkhorst. "Mass flow vs Volume Flow." Available at https://www.bronkhorst.com/en-us/service-support/knowledge-base/volume-flow-versus-mass-flow/#:~:text=In%20an%20analogous%20way%2C%20a,second%20(cm3%2Fs).

[27] Ibid.

hydrogen blending percentages above 20%, it was shown that for components that leak, the leaks were present for both 100% hydrogen and 100% methane. Likewise, repairs performed on components that leak were equally effective under 100% hydrogen and 100% methane leak tests (UCR 94).

Dispersion characteristics of hydrogen blend leaks and risk assessment

Dispersion

Dispersion is the process where a leaked or released gas cloud gradually spreads out and mixes with the surrounding air. Different gases may disperse into the surrounding ambient environment in different ways, due to both the properties of the gas being dispersed, as well as atmospheric factors like temperature, wind speed, and air pressure. For example, a light gas like pure hydrogen is very buoyant and tends to disperse vertically and quickly.[28] A heavier gas such as gasoline vapor is heavier and will tend to stay closer to the ground.[29] Studies have looked at the dispersion characteristics of hydrogen blends up to 20% and found that the dispersion characteristics are comparable to that of natural gas (UCR101, 108, 109).

Flammability Limits

Literature evaluated the lower flammability limit (LFL) of hydrogen-methane blends. The LFL is the lowest concentration of a flammable gas or vapor in air that can ignite when an ignition source (such as a flame) is present. For example, if the gas to a stove is turned on but the pilot light is not functioning for a relatively short duration of time, the released gas is at such a low concentration, the risk of auto-ignition is highly unlikely, as the natural gas volume is below its LFL.

The LFL for 100% natural gas is very similar to the LFL for a blend of 80% natural gas and 20% hydrogen (5% and 4.75%, respectively). Studies have shown that with an equivalent volumetric leak flow rate, pure methane and 20% hydrogen blends show similar behavior reaching to their LFLs, meaning they would behave very similarly, and the blend poses no significant additional risk (UCR 101).

One way to reduce the risk of hazards in case of a natural gas leak inside of a building is to ventilate the area (e.g., open windows, doors). In several studies, it was shown that the effectiveness of ventilating hydrogen-natural gas blends (up to 20% hydrogen) and 100% natural gas is similar (UCR 91,108,112).

Jet Flames

A jet flame is often used in combustion experiments to study flame characteristics under various controlled conditions. Studies evaluated the impact of blended hydrogen on jet flame characteristics such as flame length, flame color, and flame temperature. Flame characteristics can be impacted by hydrogen blends because hydrogen and methane have different chemical attributes.

Jet flames are discussed in two contexts: first, to understand impact on the operational efficiency of end-use equipment, and second, to understand if introducing hydrogen to natural gas impacts flame length, and therefore resulting "safe distance" calculations. The safety distance is the minimum separation between a hazard source and an object.[30]

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[28] The Elemental. Center for Hydrogen Safety. "Hydrogen's Buoyancy." Available at https://h2tools.org/sites/default/files/2020-10/the_elemental_on_hydrogens_buoyancy.pdf.
[29] Ibid.
[30] M. Vanuzzo, M. Carcassi. "Safety Distances: Comparison of the methodologies for their determination." Available at https://h2tools.org/sites/default/files/2019-08/paper_75.pdf.

For end use equipment, a jet flame is often used in combustion experiments to study flame characteristics under various conditions. Flame characteristics are relevant for safety and operational aspects of stoves, boilers, furnaces, and gas turbines, since combustion equipment is designed to operate within certain flame parameters. A detailed discussion on the impact of hydrogen blends on end use equipment is found in Chapter 4.

Laboratory studies on the impact of hydrogen blends on jet flame length resulting from a leaked gas found that the introduction of up to 20% hydrogen blend does not change safety design parameters for utility equipment. The report includes studies that have shown flame length decreases as the hydrogen blend increases. The decrease in the flame length is approximately 5%-6% with a 20% hydrogen blend (UCR 137, 141). A shorter flame length means that the standard safe distances used for natural gas would therefore be sufficient for 20% hydrogen-natural gas blends.

Hydrogen Blending Pilots and Demonstrations

Live demonstration pilots have studied and measured leakage for zero to 20% hydrogen by volume for the portions of the system tested. Several of these demonstration projects are summarized in the UCR Report.

The HyDeploy 2 project in the United Kingdom conducted frequent gas leak checks throughout the ten-month demonstration period. Analysis of collected data for this project suggested that 20% hydrogen blends in the distribution network did not lead to an increase of leaks identified during the project (UCR 83).

In Ireland, the HyTest project evaluated the feasibility of safely operating residential natural gas end-use equipment with blends of natural gas containing hydrogen blends ranging from 2% to 20%. Leak testing for appliances was performed for gas blends containing 2%, 5%, 10%, 15% and 20% hydrogen in natural gas at low pressure (<1 psig). The test included identifying drops in the system's pressure, which would have indicated a potential leak. These tests' findings revealed no pressure change in the tested gas lines, signifying no leaks (UCR 100).

In Spain, a consortium led by gas distribution network operator Nortegas, assessed operation of a test gas line loop representative of the Spanish natural gas distribution system. The project, referred to as H2SAREA, tested a 20% hydrogen blend for 3,000 hours. Gas leak detection checks were performed throughout the project on 552 critical points of the test loop, including flanged joints, welding, taps, valves, steel pipes, polyethylene pipes, steel-polyethylene and polyethylene-copper transitions, domestic receivers, meters, internal copper connections, appliance regulators, appliance taps and others. Gas leak tests were performed on two lines at pressures of 58 psig and 232 psig, respectively. Note, these pressures are representative of pressures seen in the California distribution pipeline system. The study concluded that no leaks were identified in the system (UCR 60).

The Hydrogen Park South Australia test evaluated gas leaks from the natural gas system after blending 5% renewable hydrogen in the natural gas network. Leak tests prior to hydrogen blending and after 12 months of operation a 5% hydrogen blend did not identify any leaks (UCR 84).

Chapter 3 – Hydrogen permeation through polymeric materials

Chapter 3 evaluates and compares the permeation rates of pure hydrogen to pure methane through plastic materials. No literature in the Literature Review quantified the permeation rates of hydrogen-methane blends. The chapter also discusses potential mitigation strategies for permeation. The literature also suggests that the occurrence of leakage has higher potential for hydrogen loss than permeation.

The following defined terms and concepts may be helpful when reviewing Chapter 3:

- **Permeation**: Permeation is the penetration of a permeate (liquid, gas, or vapor) through a solid.[31] In the case of this chapter, it refers to the penetration of hydrogen gas through a pipeline material.

Chapter 3 Key Take Aways

As research currently only compares permeation rates through plastic materials of pure hydrogen to pure natural gas, further research is still necessary regarding permeation rates pertaining to hydrogen-natural gas blends in real world operating temperatures and pressures. Demonstration projects and further lab testing can help inform this knowledge gap.

For pure (100%) hydrogen permeation through polymeric materials, the literature finds permeation of pure hydrogen through plastic pipes may occur at faster rates than that of pure methane (UCR 55). This is expected due to the smaller molecular size of hydrogen compared to methane. One study found that while hydrogen permeation would lead to more gas loss by volume, methane permeation would lead to more energy loss (UCR 4). The literature also found a relationship between the temperature of the pipe and permeation rates. One study showed that at 80ºF (300 Kelvin), pure hydrogen loss rates increase above 0.02% per year, and at 113ºF (320 Kelvin), the rate increases to nearly 0.07% per year (UCR 55). However, most plastic pipeline is buried and stays at the same temperature as the ground (approximately 50-85ºF).[32] Pressure can also impact the microstructure of polymeric materials, affecting permeation rates of either hydrogen, natural gas, or blended fuel (UCR 55).

The literature reviewed did not identify or consider whether hydrogen would separate from methane once blended and thus preferentially permeate through the polymeric material under flow regimes seen in distribution or transmission pipeline systems. Thus, additional research is needed to determine if these results are applicable to blended fuels and the conditions seen in the California gas system.

The literature review finds, "leakage mechanisms have significantly higher potential for hydrogen loss than permeation".[33] This would be expected, as permeation occurs through a solid's microstructure, while leakage is the gas escaping through an opening. Live demonstrations that address both leakage and permeation can help verify these findings.

[31] Jung JK, Lee JH, Jang JS, Chung NK, Park CY, Baek UB, Nahm SH. "Characterization technique of gases permeation properties in polymers: H_2, He, N_2 and Ar gas. Sci Rep." 2022 Feb 28. Available at https://pmc.ncbi.nlm.nih.gov/articles/PMC8885926/#:~:text=Permeation%20is%20the%20penetration%20process,following%20the%20ASTM%20D143%20standard.

[32] The mean annual soil temperature in California ranges depending on geography and type of soil, but generally, mean annual soil temperatures at a depth of 20 inches range from 50-85 degrees Fahrenheit. Soil temperature data taken from the National Cooperative Soil Survey, available at https://soilseries.sc.egov.usda.gov/.

[33] UCR Literature Review, p. 39.

Hydrogen Blending Pilots and Demonstrations

No hydrogen blending pilots or demonstrations in the published literature have reported on permeation.

Chapter 4 – Impact of hydrogen blending on heating value and end-use equipment

This chapter evaluates the impact of hydrogen-natural gas blends on a variety of end use equipment. Topics discussed include the impact of blended gas on heating value, flame characteristics, and end-use equipment operations. The impact of hydrogen blends on resulting emissions from combustion equipment is also discussed.

The following defined terms and concepts may be helpful when reviewing Chapter 4:

- **Flame Characteristics**: Flame characteristics have many components such as composition, color, temperature, burning velocity, flammability limit, flame height and flame shape.[34]
- **Flashback**: An uncontrolled upstream propagation of the flame, due to a local imbalance in the flow velocity and the flame speed.[35]
- **Gross Caloric Value**: The quantity of heat liberated by the combustion of one unit volume of gas.[36]
- **Heating Value**: Heating value, also known as calorific value, is a measure of energy that can be obtained by burning a unit of natural gas. Heating value is typically expressed in British thermal units (BTU) per cubic foot or per cubic meter. Heating value is a factor in how gas utilities determine customer billing. [37]
- **NOx:** A group of nitrogen-containing reactive gases, including nitrogen dioxide and nitric oxide. NOx species are air polluting chemical compounds.[38]
- **NOx Control Technologies:** Commonly deployed and proven NOx management technologies used in multiple industries can be considered in two groups: (1) reducing NOx formation in the combustion chamber and (2) removing NOx at the flu stack.
- **Selective Catalytic Reduction (SCR)**: SCR selectively reduces NOx emissions by injecting ammonia (NH3) into the exhaust gas upstream of a catalyst, normally before at the flu stack. The NOx reacts with NH3 and oxygen (O2) to form nitrogen (N2) and water (H2O).
- **Thermal Radiation Hazard**: Hazard posed by a thermal radiation. Thermal radiation is the phenomenon by which an object radiates electromagnetic waves due to its temperature, and it one of the three methods of heat transfer.[39]

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[34] Williams, A. Thermopedia. "Flames." February 2, 2011. Available at https://www.thermopedia.com/content/766/#:~:text=A%20premixed%20flame%20of%20a,equals%20the%20laminar%20burning%20velocity.

[35] Ali Cemal Benim, Khawar J. Syed, "Flashback Mechanisms in Lean Premixed Gas Turbine Combustion." 2015. Available at https://www.sciencedirect.com/science/article/abs/pii/B9780128007556000040.

[36] ScienceDirect. "Gross Calorific Value." Available at https://www.sciencedirect.com/topics/engineering/gross-calorific-value.

[37] Natural Gas Intelligence. "What is Heating Value?" Available at https://www.naturalgasintel.com/glossary/what-is-heating-value/.

[38] US EPA. "Technical Bulletin: Nitrogen Oxides (Nox) Why and How They Are Controlled." EPA 456/F-99-006R, November 1999. Available at https://www3.epa.gov/ttncatc1/dir1/fnoxdoc.pdf.

[39] ScienceDirect. "Thermal Radiation." Available at https://www.sciencedirect.com/topics/engineering/thermal-radiation.

- **Wobbe index**: A measure of the interchangeability of different fuels in gaseous form, indicating the changes required to the fuel system so that fuels with different heating values can be accommodated.[40]

Chapter 4 Key Take Aways

As summarized below, recent experimental studies and demonstration projects generally established the safe operation of residential and commercial end use equipment with hydrogen blends of up to 20%. Demonstration projects did not find impacts to residential and some commercial equipment performance. Combustion equipment that uses large volumes of natural gas, including industrial equipment and power plant turbines, should be evaluated on a case-by-case basis as the specific equipment design and components can vary by manufacturer and region. Thus, it is prudent to design demonstration projects that will survey impacted commercial and industrial end use equipment set to receive the blended gas and make modifications where necessary prior to blending.

Heating value, combustion, and physical properties influenced by hydrogen and natural gas blends

Heating Value

Hydrogen has lower heating value by volume than natural gas. This means that if the flow of the blended gas is constant, the time required to achieve a given temperature will take longer with a blend, than with natural gas alone. This behavior is expected due to the higher energy density of natural gas by volume. The difference in heating value can be overcome by increasing the volumetric flow of the blended gas to equipment. Blending up to 10% hydrogen by volume could meet the typical United States standard energy delivery requirements of natural gas, including gross caloric value and Wobbe index. Above 10%, the hydrogen in the blend would no longer meet current gas standard specifications. (UCR 100).

Physical Properties

Hydrogen (H_2) has different physical properties compared to methane (CH_4). Hydrogen is a smaller molecule and has lower mass, lower energy density by volume, and a lower combustion energy. The physical properties of blended gas is dependent on the percentage of hydrogen.

Combustion Properties

Combustion properties are discussed below and also addressed in Chapter 2 (jet flames).

Combustion and heating value with hydrogen and natural gas blends

Several laboratory and demonstration projects have evaluated hydrogen blends of 0-20% on a variety of end-use equipment (UCR 100,163,164,166), with mixed results. Impacts were observed when blended hydrogen was used across a variety of end use equipment. These impacts included increased thermal efficiency, overall reduction in methane consumption and CO_2 emissions, and in some cases, increased heating time (UCR 164).

[40] Taylor & Francis. "Wobbe Index." Available at https://taylorandfrancis.com/knowledge/Engineering_and_technology/Chemical_engineering/Wobbe_Index/#:~:text=The%20Wobbe%20Index%20is%20a,heating%20values%20can%20be%20accommodated.

Flame characteristics and combustion models for hydrogen and natural gas blends

Flame characteristics are relevant for both gas equipment operations and pipeline safety. Flame characteristics like flame length, flame color and vertical temperature can be impacted when blending hydrogen with natural gas. Several studies have shown that flame length decreases as the hydrogen blend increases. The decrease in the flame length is approximately 5%-6% with a 20% hydrogen blend (UCR 139, 141). This decrease in flame length does not affect the efficiency of most appliances due to the heat transfer mechanisms involved. When considering safety implications, shorter flame length would be favorable as it would reduce the safe distance required in case of a jet fire. Additionally, it was shown that thermal radiation hazard reduces slightly (~ 5%) for hydrogen blends under 20% (UCR 127).

Combustion emissions for hydrogen and natural gas

NOx is a constituent that must be considered related to the combustion process. NOx formation occurs when air, a gas mixture containing 78% nitrogen, is exposed to very high temperatures (>2,370°F)[41]. Any high-temperature combustion process can produce NOx regardless of the heat source (including diesel, gasoline, natural gas, hydrogen, and electric heat). Because hydrogen burns at higher temperatures than natural gas, studies have been conducted to better understand NOx formation when using blended hydrogen fuels.

The complex nature of combustion interactions and variability in equipment burner design means that the rate of produced NOx emissions is not necessarily proportional to the percentage of hydrogen in the gas blend. In fact, several studies indicate that maintaining a hydrogen blend below 20% may reduce NOx emissions and maintain combustion stability in certain equipment (UCR 60, 823, 100, 184). In particular, newer residential equipment with low-NOx burners have observed a reduction in NOx (UCR 184).[42]

Natural gas combustion also generates carbon monoxide and carbon dioxide emissions. Several lab experiments and a demonstration project that studied combustion of hydrogen blends less than 20% observed a decrease in carbon dioxide and monoxide, in addition to a decrease in NOx (UCR 60, 83,100,183).

At blending percentages above 20%, research indicates there may be impacts to combustion on natural gas end use equipment. These impacts may include flashback, faster flame speed, and shortened flame length. Generally, impacts to end use equipment operations related to the use of hydrogen blended gas can be mitigated with various strategies, including burner design modifications, control system adjustments, larger fuel injectors, or air-fuel mixture controls (UCR 108, 190,196).

End-use equipment operations with blended fuel

End-use equipment operations can be divided into a few categories: residential appliances, commercial/industrial end-use equipment, and power plants. As described below, common natural gas appliances have shown compatibility with hydrogen blends. One real world base case of this example is

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[41] US EPA. "Technical Bulletin: Nitrogen Oxides (Nox) Why and How They Are Controlled." EPA 456/F-99-006R, November 1999. Available at https://www3.epa.gov/ttncatc1/dir1/fnoxdoc.pdf.

[42] For example, the California South Coast Air Quality Management District has required certain combustion equipment such as residential hot water heaters and fan type furnaces sold to be low-NOx since the 1970s. Available at https://www.aqmd.gov/home/rules-compliance/rules/scaqmd-rule-book/regulation-xi.

Hawaii Gas on the island of O'ahu, which has operated a natural gas system with 12-15% hydrogen by volume for over 50 years, serving standard residential and commercial end-use appliances.[43]

Residential End Use Equipment

Residential natural gas appliances can include gas stove ranges and ovens, furnaces, water heaters, clothes dryers, grills, fire pits, and pool heaters. There are several studies and demonstration projects that found 20% hydrogen blends to be acceptable for typical end-use residential appliances (UCR 54, 60, 84). The studies and demonstration projects were carried out in several countries with different gas compositions and a variety of appliances covering a wide range of cases (UCR 86,87,100, 186).

Commercial and Industrial End Use Equipment

Industrial and commercial equipment typically require larger volumes of gas than residential appliances. This equipment may include kilns, commercial dryers, commercial boilers, furnaces, and others used in manufacturing. Recent research shows that if necessary, commercial end-use equipment may be modified to accommodate hydrogen blends up to 20% by either tuning the system or upgrading the combustion geometry (UCR 83, 162).

Power Plants

Power plants use very large volumes of natural gas to generate electricity. Generally, power plants can operate on up to 5% hydrogen blends in their existing configuration[44]. However, above 5% hydrogen, there may be impacts to the system, especially with older turbine designs. It should be noted that the allowable blending percentage may differ depending on the turbine design and manufacturer. In many cases, natural gas turbines can be modified to accommodate higher hydrogen blend percentages.

NOx emissions from power plants receiving gas blended with hydrogen are specifically addressed in the Literature Review. Although NOx formation may be higher inside the turbine reaction chamber in the presence of hydrogen gas, the resulting NOx output at the power plant flu stack must meet the same permitted limits as power plants operating at 100% natural gas. Meeting these limits is possible due to various NOx control technologies that reduce the formation of NOx altogether in the combustion chamber or remove it at the flu stack. With the proper deployment of these technologies, blended hydrogen combustion via turbines can achieve comparable performance and NOx emissions equal to or even less than today's turbines running on pure natural gas. [45]

Hydrogen Blending Pilots and Demonstrations

Several demonstration projects have considered the impact of blended hydrogen gas on various end use equipment. Generally, findings indicate that residential and light commercial appliances can operate safely and satisfactorily at up to 20% hydrogen blends without modification. For end use equipment that consumes higher volumes of gas, modifications might be required and should be considered on a case-by-case basis.

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[43] See Compendium Report Summary of Regulatory Proceedings, Table 1.

[44] U.S. EPA. "Hydrogen in Combustion Turbine Electric Generating Units Technical Support Document." EPA-HQ-OAR-2023-0072, May 23, 2023. Available at https://www.epa.gov/system/files/documents/2023-05/TSD%20-%20Hydrogen%20in%20Combustion%20Turbine%20EGUs.pdf.

[45] U.S. Department of Energy, "DOE Low NOx Targets and State-of-the-Art Technology for Hydrogen Fueled Gas Turbines," H2IQ Hour, September 2022. Available at www.energy.gov/sites/default/files/2022-12/h2iqhour-09152022.pdf.

The FutureGrid project demonstrations identified 20% hydrogen-natural gas blend as acceptable for end-use residential appliances in service within Great Britain (UCR 54). The H2SAREA project in Spain demonstrated 10% blending with no observable impacts on residential service or appliance safety and operation. The project has expanded the study to 15% and subsequently 20% hydrogen blending, with results yet to be released (UCR 60). The United Kingdom's HyDeploy 2 project evaluated a variety of industrial and commercial operations including in commercial furnaces, kilns, ovens, and boilers with 20% hydrogen blends. A learning of the study concluded, "Network operations and appliances are capable of accepting a hydrogen blend without operational constraints or issues" (UCR 83).

Ireland's HYEND project studied transmission and distribution natural gas end users for integrating hydrogen blends. The study concluded, "The survey analysis and data collected from 42 large daily metered equipment (LDMs) and a sample of 270 daily metered equipment (DMs) found that many end-users' equipment connected to the distribution network can handle a blend of up to 20% hydrogen. This information demonstrates the feasibility of introducing up to 20% hydrogen blends by volume as a viable alternative to natural gas in Ireland. Furthermore, most end users (LDM and DM) connected to transmission and distribution pipelines do not have any critical issues using a 20% hydrogen blend" (UCR 160).

In the United States, some turbine manufacturers have conducted trial tests of their gas turbines with hydrogen blends and published the findings. Mitsubishi Power and Georgia Power, alongside the Electric Power Research Institute (EPRI), successfully validated 20.9% hydrogen (by volume) fuel blending at Plant McDonough-Atkinson in Georgia on an advanced class Mitsubishi Power M501G gas turbine. The results showed that hydrogen blending increased combustion stability, reduced carbon monoxide emissions, and demonstrated the feasibility of maintaining NO_X levels similar to natural gas operation with proper fuel control adjustments (UCR 192). In another demonstration in partnership with EPRI, the New York Power Authority (NYPA) tested a General Electric (GE) turbine at 5-44% hydrogen blends. The demonstration showed that selective catalytic reduction and carbon monoxide catalyst systems were able to control the stack NO_X, carbon monoxide, and ammonia slip levels below the plant's regulatory permit limits with hydrogen cofiring (UCR 193).

Chapter 5 – Potential climate and health impacts associated with hydrogen blending

This chapter focuses on modeling and analysis performed to assess the global warming potential of hydrogen, and the potential health impact of hydrogen.
The term "climate model" is frequently used in Chapter 5. To facilitate understanding, a brief description is provided here. Climate models are computer programs that simulate weather patterns over time. By running these simulations, climate models can estimate the Earth's average weather patterns—the climate—under different conditions. Scientists use climate models to predict how the climate might change in the future, especially as human actions, like adding greenhouse gases to the atmosphere, change the basic conditions of our planet.[46]

The following defined terms and concepts may be helpful when reviewing Chapter 5:

[46] Climate Portal. "Climate Models." Available at https://climate.mit.edu/explainers/climate-models.

- **Blue hydrogen:** Hydrogen that is produced via natural gas with carbon capture, usage, and storage (CCUS).[47]
- **Climate Model:** Computer programs that simulate weather patterns over time. By running simulations, climate models can estimate the Earth's average weather patterns under different conditions. Scientists use climate models to predict how the climate might change in the future, especially as human actions, like adding greenhouse gases to the atmosphere, change the basic conditions of our planet.[48]
- **Green hydrogen:** Hydrogen that is produced from water using renewable electricity.[49]
- **Pulse event:** A "hydrogen pulse event" refers to a rapid release of hydrogen gas, often occurring in a short burst or pulse, which can be caused by various factors like a chemical reaction, electrolysis process under pulsed current or a large leak event; essentially, any situation where a significant amount of hydrogen is released in a short time frame.

Chapter 5 Key Take Aways

More research is required to understand and quantify the climate impacts of leaked hydrogen to the atmosphere and the secondary global warming potential of hydrogen. One limitation of the modeling research reviewed in the literature is that the models assume significantly higher hydrogen leak and pulse event rates rather than those observed on gas pipelines. Even so, modeling results indicate that under aggressive leakage scenarios, replacing fossil fuels with either blue or green hydrogen has a climate benefit under most scenarios in the long term.

Demonstration projects can provide value to this newer area of research because they can collect and report on actual, measured blended hydrogen leakage rates from the natural gas pipeline system. Such data can help inform and improve modeling assumptions. Note that given the relatively small amount of hydrogen that is likely to be utilized in controlled demonstration projects, climate impacts due to the potential hydrogen leakage would be negligible.

Global warming potential of hydrogen

Hydrogen itself is not a greenhouse gas, nor does it produce carbon emissions when combusted or electrochemically reacted in a fuel cell. However, recently climate modelers have begun to investigate the potential impact of hydrogen when it is released to the atmosphere.

The models observed a "secondary effect," in that hydrogen available in the atmosphere may prolong the atmospheric lifetime of methane. The mechanism behind this effect is described as follows: Normally, free hydroxyl (OH) radicals in the atmosphere oxidize methane (CH_4) molecules, helping break them down. If hydrogen is present, OH will preferentially react with the hydrogen (H_2) molecule. This can reduce the amount of OH radicals available to convert CH_4, thus causing CH_4 to linger in the atmosphere for longer.

Literature that studied climate impacts of hydrogen is based on computational and climate modeling studies, as opposed to measured and observed real world data from hydrogen operating systems. There are no known, real-world studies that measure hydrogen leakage system wide across the hydrogen value chain, from hydrogen production to pipeline transportation to end-use (UCR Chapter 5). This means that

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[47] UCR Literature Review Reference Number 200.
[48] Climate Porta. "Climate Models." Available at https://climate.mit.edu/explainers/climate-models.
[49] UCR Literature Review Reference Number 200.

climate models must rely on assumptions around hydrogen leakage, rather than observed values of real-world systems.

Nationally, the average natural gas system wide leakage rates today are below 3%.[50] Further, the leak rates for the California Natural Gas system were reported at 0.15%[51]In studies reviewed, the leakage rates assumed are not consistent with leak rates typical of natural gas pipelines. For example, one study assumes system wide leakage rates of up to 10%, which is orders of magnitude higher than measured leak rates in the California natural gas system (UCR 200).

One model looked at "pulse" events, which are defined as large, one-time leaks. The model considered atmospheric impacts of hydrogen pulse events leaking 40 million to 2.4 billion tons of hydrogen into the atmosphere (UCR201). A pulse leakage of any magnitude modeled within this range is unlikely as the global consumption of hydrogen in 2022[52] was 95 million metric tons.

In another study, Ocko et al. illustrates several leakage scenarios, 1%, 5%, and 10% leak rates. The potential warming impacts from replacing fossil fuel technologies with hydrogen alternatives were investigated under these scenarios. This study shows that even under aggressive leakage scenarios, replacing fossil fuels with hydrogen, whether blue or green, has a long-term climate benefit. The study indicates that adopting lower leak assumptions, consistent with current California natural gas system leak rates[53], will yield greater climate benefits (UCR 200).

Potential health impacts from end-use combustion of hydrogen blends

Hydrogen is non-toxic and non-poisonous. The National Fire Protection Association (NFPA) rates the health hazard components of gases on a scale of zero to four, with zero representing minimal hazard and four representing severe hazards.[54] The NFPA rates the health hazard of pure hydrogen gas as zero.[55]

Indirect impacts of hydrogen on human health have been acknowledged in the literature, especially through emissions related to combustion. This is discussed in detail under the emissions section in Chapter 4.

Hydrogen Blending Pilots and Demonstrations

The Literature Review did not contain any discussion of hydrogen blending pilots or demonstrations that directly addressed the global warming potential of leaked hydrogen in the atmosphere. With regard to

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[50] D. Kirchgessner, R. Lott, R. Cowgill, M. Harrison, T. Shires. U.S. EPA, "Estimate of Methane Emissions from the U.S. Natural Gas Industry." Available at https://www.epa.gov/sites/default/files/2020-11/documents/methane.pdf.

[51] CPUC and California Air Resources Board. "Analysis of the Gas Companies' June 14, 2024, Natural Gas Leak and Emission Reports." Available at cpuc.ca.gov/-/media/cpuc-website/divisions/safety-policy-division/reports/2024-ngla-joint-report_122424.pdf.

[52] International Energy Agency. "Global Hydrogen Review 2023", p. 64. Available at https://iea.blob.core.windows.net/assets/ecdfc3bb-d212-4a4c-9ff7-6ce5b1e19cef/GlobalHydrogenReview2023.pdf.

[53] CPUC and California Air Resources Board. "Analysis of the Gas Companies' June 14, 2024, Natural Gas Leak and Emission Reports." Available at cpuc.ca.gov/-/media/cpuc-website/divisions/safety-policy-division/reports/2024-ngla-joint-report_122424.pdf.

[54] NFPA. "Hazardous Materials Identification." November 5, 2021. Available at https://www.nfpa.org/news-blogs-and-articles/blogs/2021/11/05/hazardous-materials-identification.

[55] Cameo Chemicals. "Hydrogen." Available at https://cameochemicals.noaa.gov/chemical/8729.

human health and climate impact of blended hydrogen in the gas system, generally, the demonstrations found that use of hydrogen reduced carbon dioxide emissions and methane consumption. Additionally, some demonstrations looked at combustion emissions related to the use of blended hydrogen in end use equipment. These results are discussed in Chapter 4.

Chapter 6 - Hydrogen Leak Detection, Monitoring and Control

Natural gas pipeline leak detection, monitoring, and control involves utilizing various technologies to identify and measure potential leaks along a pipeline by monitoring pressure, flow rate, and acoustic (sound) signals. This enables rapid response and mitigation actions to enable safe, reliable operation and minimized environmental impacts.

This chapter reviews recent findings on gas leak detection techniques, pipeline operations and repair activities, and behavior of hydrogen leaks in homes.

Chapter 6 Key Take Aways

As summarized below, one modeling study and several experimental studies have investigated leak detection, control, and mitigation methods for hydrogen blends ranging from 0-20%, above 20%, and up to 100% hydrogen. This research suggests that computational pipeline monitoring systems, existing maintenance and operation procedures, odorant, and standard repair methods can be utilized in traditional natural gas pipeline infrastructure with hydrogen blends up to 20% by volume. Of these studies, only one identified pilot project included research on hydrogen blends below 20%. This review highlights the need for demonstration projects that can replicate the conditions and varied environments of California's natural gas infrastructure, as research is still necessary for leak detection, control, and mitigation, particularly under real-world operating conditions.

Gas Leak Detection Techniques

Sensor-Based Detection of Hydrogen

Sensor-based detection of hydrogen measures the concentration of hydrogen present in air. Thus, these sensors are most effective when sited close to a leak origin, making them more suitable to enclosed areas. Sensors do not measure leak flow rate. In addition, as these sensors are for pure hydrogen detection, they can be used in pure hydrogen applications, such as production facilities, storage facilities, and interconnection points along the natural gas system. For lower hydrogen blends (below 20%), existing natural gas sensors or modified sensors that can detect both methane and hydrogen may be more suitable. However, further research is needed to understand the compatibility of existing natural gas sensors with hydrogen blends.

Various types of sensors were evaluated in the literature, comparing their pros and cons, including their ability to detect various hydrogen blends up to 100% hydrogen, accuracy, cross-sensitivity, and cost-effectiveness. For instance, one study suggested using specific metal oxide sensors for hydrogen blends, which detect changes in electrical resistance with temperature modulation (UCR 211). Experimental work in the HyDeploy project in United Kingdom evaluated different leak detectors for hydrogen blends up to 20% through experimental work. The study showed that some natural gas and carbon monoxide (CO) detectors are cross-sensitive to hydrogen (UCR 212). Cross-sensitivity refers to a sensor's ability to detect gases other than the specific one it is designed to monitor, which can lead to false readings.[56] More research is needed to evaluate mitigation measures for cross-sensitivity and understand sensor performance in mixtures of hydrogen and natural gas, particularly under real-world conditions.

Odorization

Another common method for detecting leaks is to add an odorant to the gas mixture, which is standard practice today and gives natural gas its characteristic "rotten egg" smell. Studies in Europe have evaluated the compatibility of common odorants with hydrogen blends and 100% hydrogen, showing that existing odorants can be effective when used with hydrogen blends (UCR 50, 91, 213, 214, 215). Notably, one of the odorants studied was tetrahydrothiophene (THT), which is used alongside tert-butyl mercaptan (TBM) in California's gas system and was shown to be compatible.

Computational Pipeline Monitoring

Computational pipeline monitoring systems are another well-established leak detection method for natural gas systems. This method utilizes computer algorithms to detect leaks by monitoring changes in pipeline data (e.g., pressure and flow rate), including the Supervisory Control and Data Acquisition (SCADA) system, which collects data via pipeline sensors. A study has shown that it can also be effective for detecting leaks of hydrogen blends when the gas blend composition is known (UCR 208). Gas composition is typically measured at various points along the natural gas system.

Pipeline Operations and Repair Activities

Natural gas pipeline operations and repair activities promote safe and efficient gas transportation. Routine continuous monitoring with SCADA systems tracks real time pressure and flow rates, while regular inspections using drones and in-line tools identify matters like corrosion and leaks so that it can be promptly repaired. Standard maintenance activities include cleaning pipelines and monitoring equipment such as compressors, valves, meters and regulators, so it operates correctly. Control centers provide 24/7 situational awareness of the entire natural gas network, managing operations and facilitating rapid response to events.

Most studies have determined that hydrogen blends below 20% do not require significant changes to standard maintenance and operations.[57] Further research can test these findings under real-world conditions for the California gas system.

Scenario Evaluation of Confined Domestic Hydrogen Gas Leaks

Research is needed to evaluate the behavior of hydrogen leaks in homes, particularly with hydrogen blends. Only one such study was found in the literature that evaluated 100% natural gas versus 100% hydrogen and found that it can be made as safe as natural gas in common residential buildings (e.g., detached, etc.) (UCR 91).

Gas Leak Mitigation

Natural gas pipeline leak mitigation involves continuous monitoring with SCADA systems, regular inspections, and/or employing robust repair techniques. Odorants can be used to detect leaks early, and

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[56] Industrial Scientific. (n.d.). "Electrochemical Gas Sensor Cross Interference Table." Available at https://www.indsci.com/en/blog/electrochemical-sensor-cross-interference-table.

[57] Literature Review. "Pipeline Operations and Repair Activities", p. 84.

advanced technologies like automatic shut-off valves help to isolate leaks quickly. Experimental research conducted thus far has shown that the standard repair methods for leaks were equally effective for hydrogen blends under 20%, provided that the materials are compatible with hydrogen (UCR 94).

Hydrogen Blending Pilots and Demonstrations

The pilot project Hydrogen Park South Australia (HyP SA), which is delivering 5% hydrogen blends to approximately 700 residential and commercial customers, showed that odorant levels were not impacted and still effective (UCR 84).

Chapter 7 - Impacts on Natural Gas Storage Fields

While Chapters 1-6 cover various aspects of natural gas pipeline infrastructure, Chapter 7 focuses on natural gas storage fields. Pipelines transport natural gas to end-users, while storage fields, such as depleted natural gas reservoirs, store natural gas to balance supply and demand across seasons. Unlike with pipeline infrastructure, there is less research on the impacts of natural gas blended with hydrogen for natural gas storage fields. The existing literature primarily focuses on pure hydrogen storage. Since research on storing blended hydrogen is still in its early stages, it is unclear how much of the research on 100% hydrogen storage systems can be applied to blended storage in natural gas fields. It is also important to note that the California Energy Commission has launched a grant funding opportunity to evaluate the feasibility of using existing underground gas storage facilities to store clean renewable hydrogen.[58]

The topics covered by this chapter include operations and modifications to storage fields, sealability, well integrity, microbial responses, and geomechanics.

Chapter 7 Key Take Aways

Research on storing blended hydrogen in depleted gas reservoirs is still in its early stages. Most studies have focused on pure hydrogen storage, utilizing computer modeling and laboratory experiments. To bridge operational knowledge gaps, further evaluation is essential to replicate the conditions and environments of California's depleted gas reservoirs.

Operations and Modifications to Storage Fields

Literature has studied the operations of depleted gas reservoirs to varying degrees and at different blend levels, including below 20%, above 20%, and at 100% hydrogen. As hydrogen is lighter (less dense) and flows more easily (lower viscosity) compared to natural gas, alternative strategies may be needed for effective management of these elements in blended hydrogen natural gas storage. Frequent adjustments in operational cycles, especially injection and withdrawal cycles, can enhance hydrogen recovery by counteracting hydrogen's buoyancy and rapid migration (UCR 222). Strategic well placement and injection techniques can manage hydrogen's behavior and reduce migration risks (UCR 224). Additionally, fiber-optic sensors can be employed in the wellbore for early leak detection (UCR 197). Infrastructure upgrades, particularly in well completion materials, may be necessary to enhance durability (UCR 161).

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[58] See California Energy Commission. "GFO-253-503- Feasibility of Underground Hydrogen Storage in California." available at https://www.energy.ca.gov/solicitations/2024-04/gfo-23-503-feasibility-underground-hydrogen-storage-california.

Sealability and Well Integrity

Sealability

Sealability in depleted gas reservoirs refers to the ability of the reservoir's caprock (sealing layer) to prevent the escape of stored gas. An effective seal is necessary to maintain integrity and containment of the gas long term.

Literature focused on studying sealability for 100% hydrogen storage looking at unconventional gas reservoirs, which are typically reservoirs with low permeability (UCR 228). For conventional gas reservoirs, it was noted that depleted gas reservoirs offer favorable storage conditions for 100% hydrogen. However, further research is required to understand impacts to material integrity, well casings, and sealing materials under cyclic loading (UCR 229). Additional research is required for blended hydrogen storage to understand potential impacts to sealability.

Well Integrity

Well integrity refers to the safe storage of gas by maintaining the wellbore's structural soundness and facilitating efficient gas extraction. One study discussed well integrity mechanisms that present challenges common to natural gas storage and hydrogen storage. The study proposed well completion criteria and material selection as mitigation measures (UCR 220). The importance of continuous monitoring was emphasized, along with the need for further research to study hydrogen's impact and improve well integrity management in 100% hydrogen underground storage systems (UCR 220). For blended hydrogen storage, additional research is required to understand potential impacts to well integrity.

Microbial Response and Other Challenges

Microbial Response

Native microbial communities in depleted gas reservoirs can interact with the stored gas, leading to various biochemical reactions, and every reservoir has a unique microbial community.

Environmental factors that influence microbial growth include temperature, salinity (amount of salt dissolved in water) and pH. By adjusting these conditions to levels that are unfavorable for microbes, their populations can be managed and reduced.

Literature focused on studying microbial responses in 100% hydrogen storage. For example, literature looked at methanogens that consume stored hydrogen and produce methane, reducing hydrogen purity (UCR 230) and sulfate-reducing bacteria that produce hydrogen sulfide, posing a corrosion risk to metallic components like steel casings (UCR 220). Research is required to understand microbial responses and develop mitigation strategies for blended hydrogen natural gas storage.

Other Challenges

The geomechanics of depleted gas reservoirs involve understanding how the physical and mechanical properties of the reservoir rock and surrounding formations change as gas is extracted. Literature noted that for 100% hydrogen storage, there is limited understanding of geomechanical effects of injection and withdrawal cycles (UCR 225), requiring further studies to assess how repeated pressurization cycles may impact reservoir integrity and hydrogen retention over time (UCR 220). Research is required to understand potential impacts to the geomechanics of depleted gas reservoirs for blended hydrogen natural gas storage.

Hydrogen Blending Pilots and Demonstrations

No hydrogen blending pilots or demonstrations on underground storage have been reported in the literature published from July 2022 through August 2024.

Hydrogen Blending with Natural Gas Literature Review – Prepared by University of California, Riverside

Hydrogen Blending with Natural Gas Literature Review

DATE: 2/10/2025

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SCOPE AND DEFINITIONS

Following the publication of the Hydrogen Impacts Study, the independent report by the UC Riverside research team in 2022 (*1*), the California Public Utilities Commission (CPUC) issued decision D.22-12-057[1] directing the Joint Utilities to file a Blending Compendium Report that reviews the literature on hydrogen blending with natural gas published since then and to include findings related but not limited to the following topics:

1. Safety performance, safety thresholds, and integrity threat levels on various pipeline network components associated with hydrogen injection, at various hydrogen blend percentages.
2. Leakage rates of the methane and hydrogen blend compared to pure methane.
3. Modeling to quantify lost hydrogen due to leakage.
4. Hydrogen permeation rates through polymer materials as compared to the natural gas permeation rates, and assessment of technologies for preventing or mitigating methane and hydrogen blend leakage in polymer and other pipeline materials.
5. Impact on storage fields, and modifications that may be necessary to maintain safety.
6. Analysis of the best equipment to monitor, detect, and control hydrogen leakage, and assessment of new hydrogen leak detection technologies.
7. Analysis of the impact of hydrogen dilution on heating value, and the required modifications of end-user equipment and appliances.
8. Any and all human health issues identified.

Pursuant to the directive in D.22-12-057, the Hydrogen Blending Compendium Report presented here was commissioned by the following California Investor-Owned Utilities (Joint Utilities): Pacific Gas and Electric Company (PGE), San Diego Gas & Electric Company (SDG&E), Southern California Gas Company (SoCalGas), and Southwest Gas Corporation (Southwest Gas).

This report provides a review of research studies, reports, and other relevant materials published from July 2022 through August 2024, covering the literature published since

[1]Decision 22-12-057, December 15, 2022: Decision directing biomethane reporting and directing pilot projects to further evaluate and establish pipeline injection standards for clean renewable hydrogen.
https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M500/K055/500055657.PDF

the release of the 2022 UC Riverside study. However, several studies outside of this period are referenced in the report where necessary to provide additional context or background information. The search for relevant scientific journal articles and conference proceedings was conducted using the Web of Science database, through a combination of keywords and keyphrases, contained within the titles or abstracts of publications. The search for relevant reports was performed using the same keywords and keyphrases via Google search engine. The search results were then reviewed for relevance to the listed topics and the contents and findings are discussed in the report. A number of articles and reports that met the search criteria are not directly referenced in the main report. These articles and reports are either focused on topics not relevant to the scope or they reported findings covered in greater depth by other references. These articles and reports are however listed in Appendix A for reference purposes.

The scope of the review encompasses topics related to the blending of hydrogen into the existing natural gas infrastructure, including transmission, compression, pressure regulation, metering, distribution, storage, and common end use equipment and appliances. The review does not cover topics of hydrogen generation, technologies for separation of hydrogen from natural gas, pure hydrogen use applications, economic impacts, and cost analysis of hydrogen blending. Articles related to hydrogen's indirect global warming potential are reviewed but literature related to the broader greenhouse gas (GHG) reduction potential of hydrogen blending into natural gas has been excluded. Specific use cases, regulations, or circumstances that are not applicable to natural gas utilities in the State of California are not included in the report. However, scientific literature and findings that may not be directly relevant to the Joint Utilities' proposed blending activities are discussed where necessary to provide context regarding hydrogen's impacts on materials and equipment.

Literature evaluating the impacts of both hydrogen – methane and hydrogen – natural gas blends are included in the review. The discussion includes information on which blend was used in each article or report. As methane is the primary component of natural gas, the results from the studies on hydrogen - methane blends are considered applicable to hydrogen - natural gas blends. Since the review includes international publications in addition to US publications, a combination of international (SI) and imperial units of measurements are used. Where possible, imperial units are provided in parentheses, with the exception of graphs and tables. Blending concentration of hydrogen in methane or natural gas is on volumetric bases, which is also equivalent to molar concentration. Gas flow rates are typically presented on a volumetric basis. However, there are some instances where flow rates are shown on mass or energy basis. These are explicitly stated and also indicated by the units used. The pressure values represent pressure relative to atmospheric pressure.

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EXECUTIVE SUMMARY

This report provides a review of the scientific literature published between July 2022 and August 2024 on topics related to blending hydrogen gas into natural gas infrastructure. The review covers publicly available material including peer reviewed research articles, project reports, and other relevant documents published during the review period, with an emphasis on material more relevant to California's natural gas infrastructure. The review focuses on the topics of importance identified in the California Public Utilities Commission (CPUC) directive D.22-12-057, and listed in the 'Scope and Definitions' section of this report. The purpose of this report is to provide a summary of the scientific findings and knowledge gaps identified in the literature during the review period that are most relevant to the listed topics.

The reference materials reviewed in this report include data and findings from laboratory experimental research, modeling analysis, demonstration projects and pilot projects of various scales and geographical locations. The reported findings should be considered within the context of the purpose, scope, parameters and assumptions employed by the specific studies. As an example, laboratory experiments and numerical studies may not necessarily capture the broad range of real-world operating parameters and environments, or consider all possible influencing factors. Some research studies are focused on elucidating fundamental properties or mechanisms, and therefore may employ different experimental or modeling conditions and parameters that would accelerate or strengthen specific effect or behavior. For instance, a number of studies employ significantly higher pressures and temperatures than are encountered in the natural gas infrastructure to evaluate material properties and other characteristics. The review also includes studies that evaluate a broad range of blending percentages while the Joint Utilities' hydrogen blending tests are proposed to not exceed hydrogen blends of 20%.

The report is divided into seven chapters, each covering the following topics: 1. Impact of hydrogen blends on materials, pipeline network components and associated safety and performance thresholds, 2. Leakage rates of methane and hydrogen blends, and hydrogen loss due to leakage, 3. Hydrogen permeation through polymeric materials, 4. Impact of hydrogen blending on heating value and end-use equipment, 5. Potential climate and health impacts, 6. Leak detection, monitoring, and control, and 7. Impacts on natural gas storage fields. Each chapter includes a discussion of the relevant articles and reports, and incorporates tables and figures and other data from those publications when necessary. Findings and recommendations from specific references are included in the discussion. This information should be considered within the context of the specific study, rather than as conclusive evidence relating to the broader topic or associated operational and safety aspects. The reader is encouraged to review the specific references for additional details on the purpose, assumptions, parameters, findings and other aspects of the study.

The following paragraphs of this section provide an overview of the specific topics reviewed in the report. An important focus area of the literature is on the impacts of hydrogen on materials commonly used in the natural gas infrastructure. These include pipeline carbon steel materials such as the API 5L group, different varieties of polyethylene that are commonly used in distribution pipelines, and elastomer materials such as nitrile rubber (NBR), ethylene propylene diene monomer rubber (EPDM), and vinylidene fluoride (FKM) that are commonly used in gaskets and seals. The results provide further insights into the properties and behavior of these materials in the presence of hydrogen including the detrimental impacts described in the Hydrogen Blending Impacts Study, including embrittlement of metals and associated reduction in strength and toughness, and a reduction in the creep performance and material integrity limitations of polymers(*1*). Potential strategies to mitigate such impacts have also been reported. Limited data is available on the impact of hydrogen on thermoplastic materials such as polyamide (PA), polyvinyl chloride (PVC), and acrylonitrile butadiene styrene (ABS).

Potential changes to operational parameters of gas compression, gas transport, and other infrastructure components due to the different thermophysical properties of hydrogen compared to methane have been evaluated in the literature. The transport and delivery of an equivalent amount of energy by hydrogen blended natural gas in the existing infrastructure would require increased compression rates. The temperature changes observed in pressure regulators and valves in use with natural gas are expected to be altered under operation with hydrogen blended natural gas due to the different Joule-Thompson coefficients of hydrogen and natural gas. The extent of the impact of hydrogen blending on operability and accuracy of natural gas meters will greatly depend on the specific meter type and operating parameters.

A number of experimental and modeling studies have reported that the volumetric basis leak flow rates from existing leaks increase when hydrogen is blended with natural gas or methane under the same conditions. The gas dispersion or accumulation characteristics of hydrogen-blended natural gas released due to a leak depend on whether the release occurs in open or confined space, the volume of the space, ventilation characteristics, leak rates and the concentration of hydrogen in the gas mix.

Indirect impacts of hydrogen on human health have been acknowledged in the literature, especially through combustion emissions. Hydrogen blended gas has a lower energy content compared to an equivalent volume of natural gas, along with differences in properties, which can be estimated using the hydrogen percentages. These properties can affect combustion temperatures, flue gas composition, and other factors relevant to end use applications. The review covers industrial, commercial, and residential natural gas equipment including gas turbines, furnaces, boilers, ovens, and cooktop end-uses. Universal trends in combustion emissions have not been observed due to the significant variability of end-use appliance design, combustion regime, and operational conditions. Studies suggest that appropriate end-use appliance design and operational strategies may significantly mitigate NO_X concerns for many applications. Recent studies have also focused on the indirect climate impacts of hydrogen when directly released into the atmosphere. This is due to hydrogen reacting with OH radicals and consequently prolonging the atmospheric lifetime of methane, a potent GHG.

A number of hydrogen detection sensors have been evaluated in the literature. Semiconductor metal oxide sensors are commonly used and are cost-effective, though they have lower accuracy and are affected by humidity and temperature. Thermal conductivity sensors offer the widest measurement range and the highest accuracy, but can have cross-sensitivity with helium. Catalytic sensors have a broad hydrogen detection range, but are less selective for hydrogen. Odorization with a commonly used natural gas odorant like tetrahydrothiophene, as well as sulfur-free odorants Gasodor S-Free and 2-hexyne have been shown to be applicable for pure hydrogen gas. Pilot projects blending hydrogen in natural gas at up to 20% at the distribution network have not observed impacts of hydrogen on odorization.

Regarding the storage of hydrogen blends in underground natural gas storage facilities, studies have focused on hydrogen's mobility, microbial activity, and complex interactions with geological formations and infrastructure and challenges associated with using the types of underground storage facilities in currently in use in California to store hydrogen or methane hydrogen blends.

The literature includes a number of publications from ongoing and recently completed demonstration projects aimed at evaluating the impacts of blending hydrogen into local natural gas infrastructure and associated systems. These projects, especially those employing hydrogen percentages of 20% or lower, have not reported major challenges related to safety and performance characteristics of materials or components. The research, development, and demonstration efforts published during the review period show that incremental knowledge has been accrued during the review period on important topic areas. Overall, the review shows that there is a need for demonstration projects that can simulate the conditions and environments of California's natural gas infrastructure as knowledge gaps exist, especially under the real-world environments that systems operate under.

CHAPTER 1: Impact on materials, pipeline network components and associated safety and performance thresholds

Blending of hydrogen gas (H_2) in the existing natural gas infrastructure presents multiple challenges due to its different thermophysical properties in comparison to natural gas, and its higher reactivity with materials and unique ability to change mechanical properties of some materials. This chapter provides a review of recent findings on the subject of impacts of hydrogen blended natural gas on common materials used in the natural gas infrastructure. The review includes impacts of hydrogen blending on components in the natural gas network including valves, pressure regulators, and meters.

Impacts on pipeline materials

Pipeline steels

Essentially all natural gas transmission pipelines in California, with minor exceptions, and roughly half of natural gas distribution network are made of steel. Steel grades commonly used in pipelines include API 5L Grades A, B, X42, X46, X52, X56, X60, X65, X70, X80, and higher strength grades (*2*). Although the impacts of hydrogen on the mechanical properties of these steels have been studied extensively under different conditions such as partial pressure, temperature, and exposure duration, there are other factors such as the age of steel pipes, material defects, manufacturing methods, operating environments, and existing structural damage which can have an influence (*3*). The general impacts of hydrogen gas on mechanical properties of steel are increased fatigue crack growth rate[2], reduced fracture toughness[3], and reduced ductility (*4*–*6*).

Fatigue crack growth rate can be accelerated even at small partial pressures of hydrogen such as 1 bar (14.5 psi); however, it generally increases with increasing hydrogen concentration and it is more pronounced at higher stress levels (*3*). Testing of steel specimens in accordance with ASTM standard E647 with load frequency[4] of 1 Hz

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[2] Indicates rate at which a crack propagates through a material due to cyclic loading.

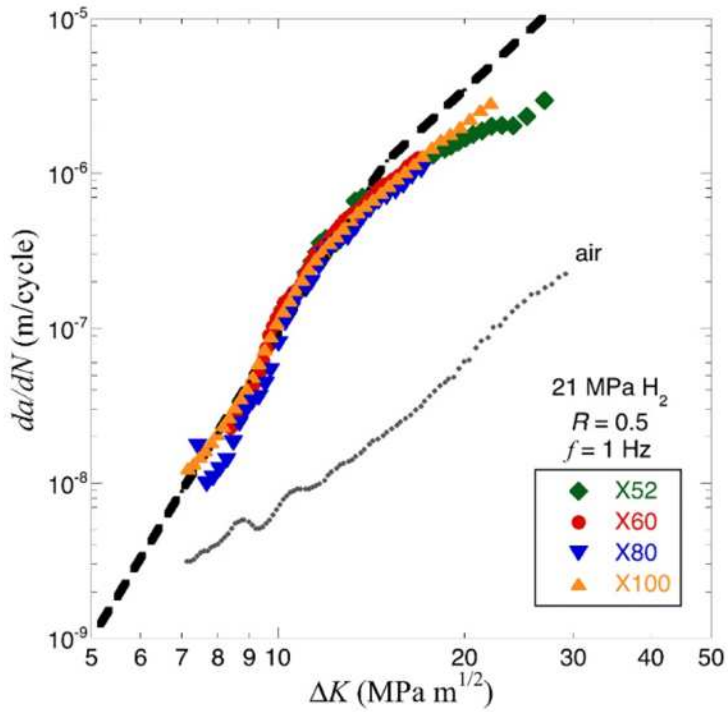
[3] Ability of a material to resist propagation of flaws when subjected to a stress or load.

[4] The rate at which cyclic loading is applied.

has shown that fatigue crack growth rate in steel can be 10 times higher in a test environment of 5% hydrogen in nitrogen compared to pure nitrogen (*7*). However, since the impact of hydrogen on physical properties of metal is a product of both pressure and concentration of hydrogen in the gas blend, it is typically presented in terms of hydrogen partial pressure (*5*). Thus, steel used in a transmission pipeline operating at a higher pressure than a distribution pipeline would experience both greater stress and higher hydrogen partial pressure than the steel of a distribution pipeline under the same hydrogen blending concentrations.

Experimental work conducted by Sandia National Laboratory has demonstrated that hydrogen exposure at pressure of 21 MPa (3046 psi) accelerates fatigue crack growth rates in API 5L grade steels (*3*, *8*). The different strength grade steels tested (X52, X60, X80, X100) all show a similar trend in increase of fatigue crack growth rates (da/dN), as shown in Figure 1, where hydrogen partial pressure is 21 MPa (3046 psi), load ratio[5] R is 0.5, and loading frequency is 1 Hz.

Figure 1: Fatigue crack growth in different API 5L steels exposed to hydrogen (*3*)



Kappes and Perez summarized effects of hydrogen partial pressure on fatigue crack growth rate in various API 5L steel grades (Table 1) (*9*). It can be seen that fatigue crack growth rate under relatively modest partial pressures of hydrogen such as 0.1 to

[5] The ratio of the maximum and minimum stress intensity factors during a load cycle.

0.7 MPa (14.5 to 102 psi), are about an order of magnitude greater compared to those under air.

Loading frequency and pressure have been shown to influence fatigue crack growth in steels exposed to hydrogen (*10*, *11*). Reduction in loading frequency and increased pressure accelerate fatigue crack growth in hydrogen environment.

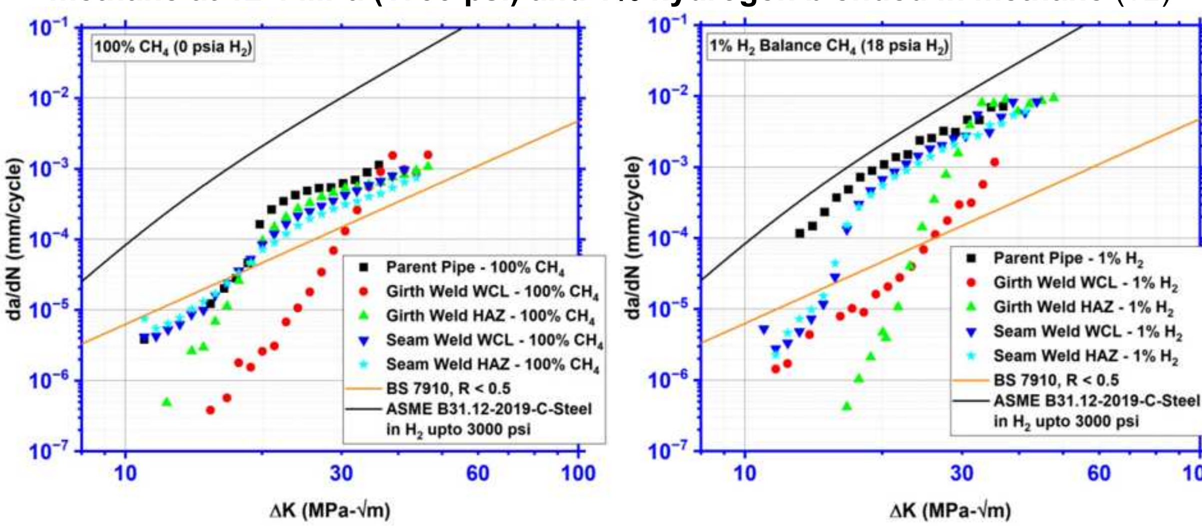
Table 1: Effect of hydrogen partial pressure on fatigue crack growth rate (*9*)

Grade	da/dN_{H2}	da/dN_{air}	p H_2	ΔK	R	References
	mm/cycle		MPa	MPa $m^{1/2}$		
API 5L X42	1.4×10^{-3}	1.4×10^{-4}	0.2	22	0.25	Holbrook et al. (1982)
SM490B (0.16 wt% C, S_y = 360 MPa)	7×10^{-4}	5×10^{-5}	0.7	20	0.1	Yoshikawa et al. (2014)
API 5L X70	8×10^{-4}	10^{-4}	0.1	30	0.1	Nguyen et al. (2021a)
API 5L X80	4×10^{-3}	2×10^{-4}	0.6	40	0.1	Meng et al. (2017)
API 5L X52	3×10^{-3}	$4{,}6 \times 10^{-4}$ [a]	0.6	30	0.1	Ronevich and San Marchi (2021)
API 5L X70	2×10^{-4}	2×10^{-5}	0.123	16	0.3	Chandra et al. (2021)

[a]Not reported in reference. Calculated with Paris law, Equation (10).

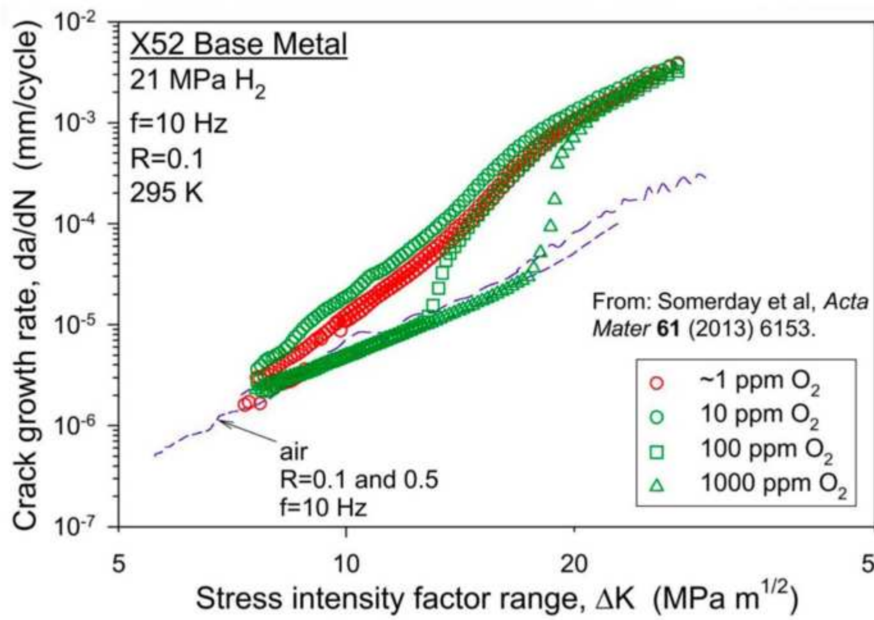
Chandra *et al.* evaluated fatigue crack growth on X52 steel, girth and seam welds and their associated weld center lines (WCLs) and heat-affected zones (HAZs), in pure methane (CH_4) (Figure 2 left), 1% (Figure 2 right), 5% and 10% hydrogen in methane (*12*). The addition of hydrogen increased fatigue crack growth rate, even at 1%, compared to tests under pure methane.

Figure 2: Fatigue crack growth rate of X52 steel and welds, subjected to pure methane at 12.4 MPa (1799 psi) and 1% hydrogen blended in methane (*12*)



Investigations of the impacts of hydrogen gas on fatigue crack growth in steels are ongoing and new findings are continuously added to the body of scientific knowledge. The adverse effects of hydrogen and the corresponding fatigue crack growth rates have been shown to be reduced by the inclusion of certain gas impurities, such as carbon monoxide and oxygen (*4*). Figure 3 shows the impact of oxygen impurity at various concentrations in hydrogen, on fatigue crack growth rate in X52 steel, subjected to 21 MPa (3046 psi) pressure. It can be seen that the addition of 100 parts per million (ppm) and 1000 ppm oxygen (O_2) both reduce fatigue crack growth rate at low stress levels (*6*). Additionally, it has been also shown that water impurity present in hydrogen gas can impede the effect of fatigue crack growth rate (*13*). On the other hand, the addition of hydrogen sulfide (H_2S) and methanethiol (CH_3SH) to hydrogen gas promotes fatigue crack growth (*14*).

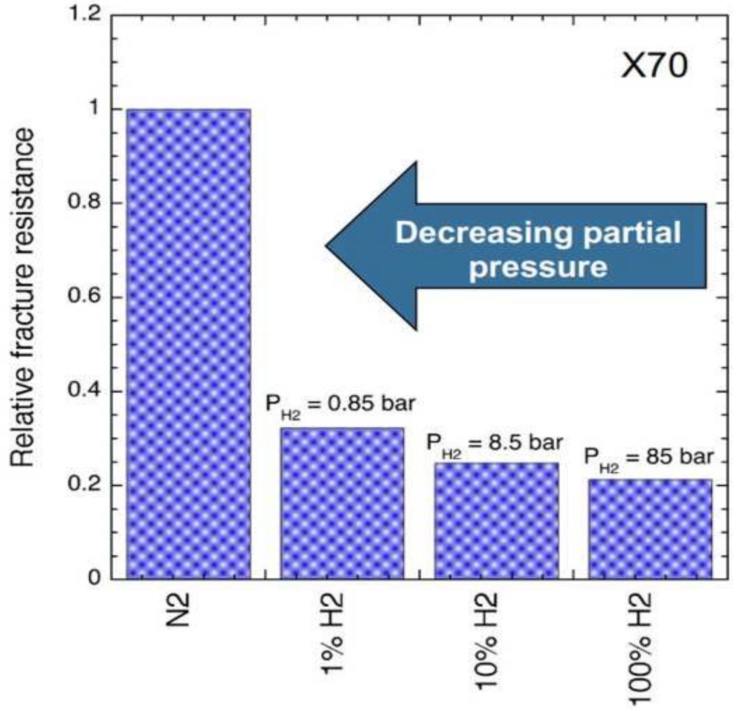
Figure 3: Effect of oxygen impurities in hydrogen gas on the crack growth rate in X52 steel (*6*)



In addition to impurities in hydrogen, modifications in steel microstructure surface treatments have also been reported to potentially reduce the detrimental effects of hydrogen (*15*). These include microstructure changes through annealing and heat treatment, and surface treatments like electroplating and shot peening (*16*), and applications of polymeric coatings and liners (*17–20*).

Hydrogen has been known to reduce fracture resistance (or toughness) in API 5L steels. Figure 4 shows that even small partial pressure of hydrogen can reduce fracture resistance of X70 steel, relative to test results under nitrogen environment (*8*).

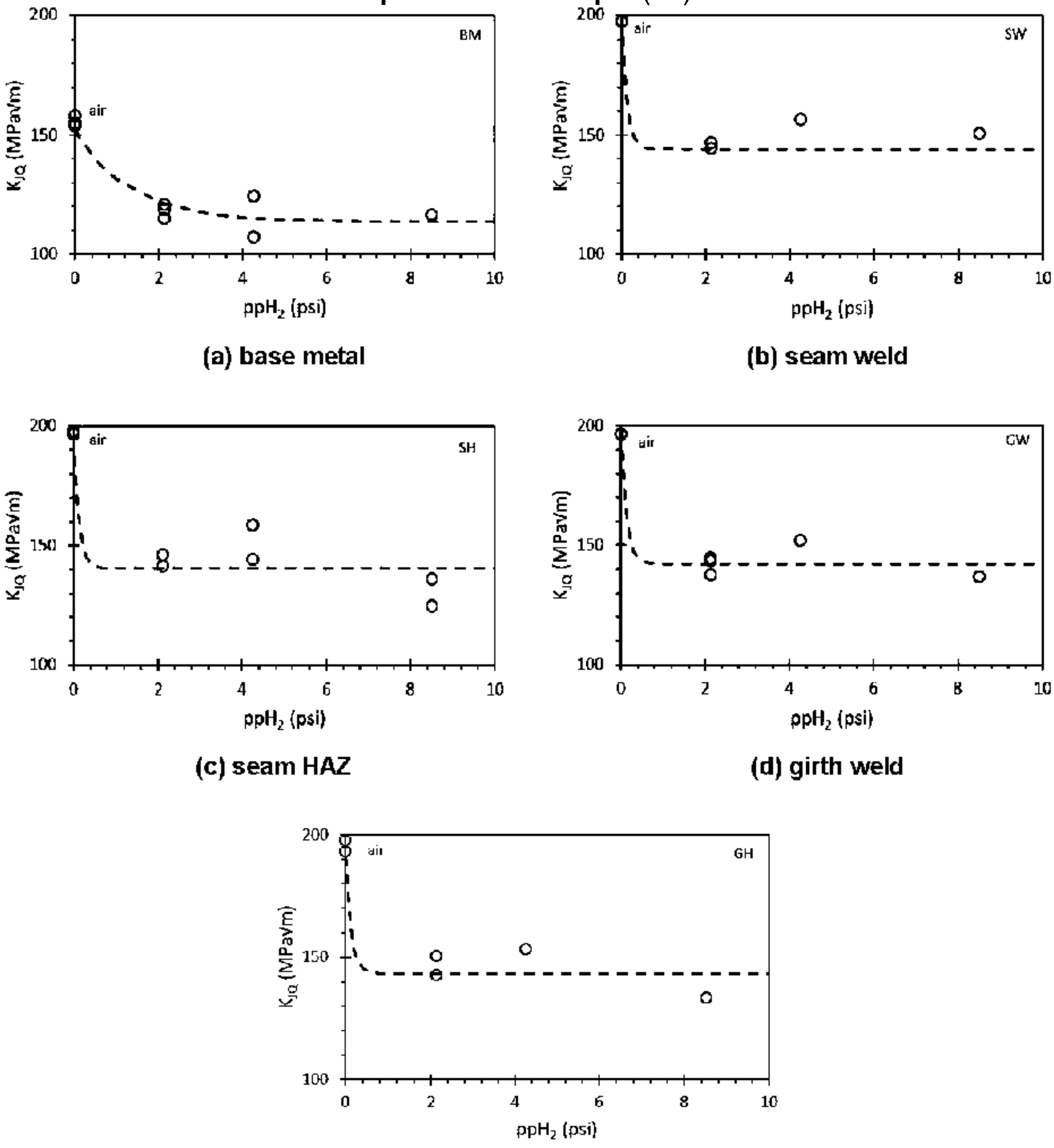
Figure 4: Fracture resistance of X70 steel at different pressures of hydrogen (*8*)



Legacy X52 pipeline steel testing for compatibility with hydrogen service were conducted by Southwest Research Institute, including fracture toughness tests at various hydrogen partial pressures (*21*). Figure 5 shows fracture resistance (K_{JQ}) in base metal, seam weld, girth weld, and their associated heat-affected zones, in air and different partial pressures of hydrogen. Fracture resistance is plotted as a function of partial pressure of hydrogen at total gas pressure of 800 psi, resulting in hydrogen concentration from 0 to 1.2%. In all tested material samples, the fracture resistance is reduced by roughly 25% with hydrogen compared to tests in air.

Agnani *et al.* evaluated fracture resistance under hydrogen environment in three vintage X52 steels, from 1950, 1959, and 1962 (*22*). Figure 6 shows the results from fracture toughness measurements in base material and welds, where B50, Y59, N62 indicate the vintage year. The results suggest reduction of fracture resistance in all three vintage steels under hydrogen exposure, which is more prominent at higher hydrogen pressures.

Figure 5: Fracture toughness at different partial pressures of hydrogen, at total pressure of 850 psi (*21*)



(a) base metal

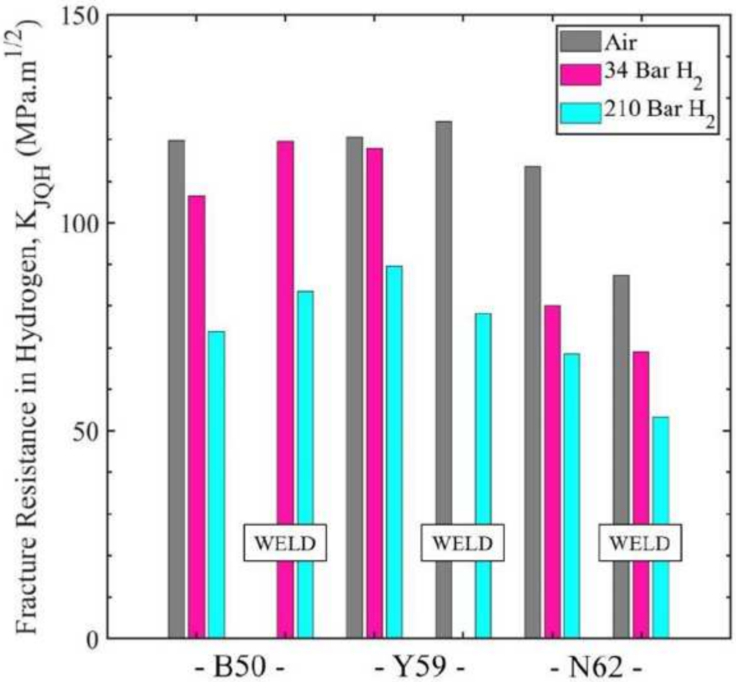
(b) seam weld

(c) seam HAZ

(d) girth weld

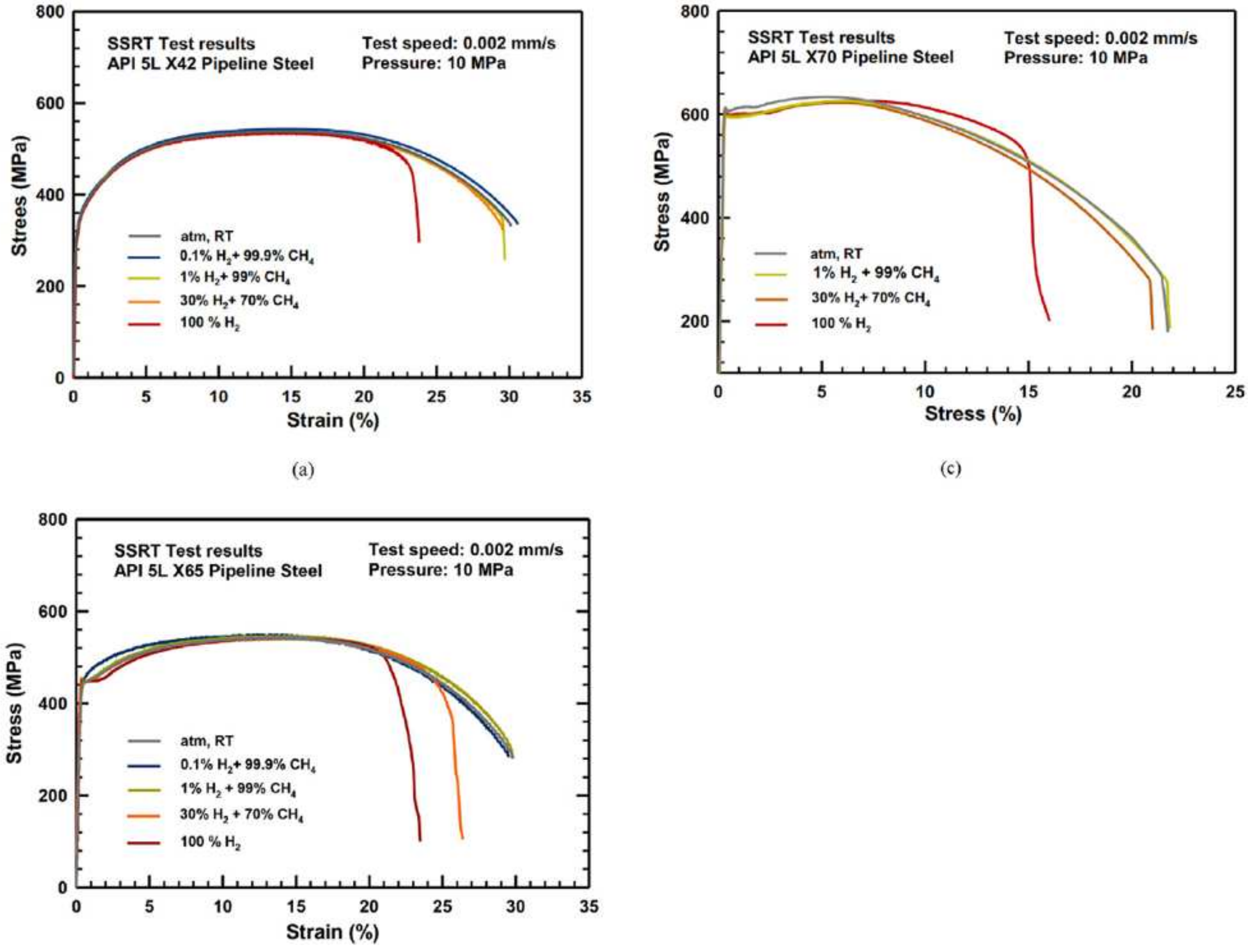
(e) girth HAZ

Figure 6: Fracture resistance of X52 vintage steels in hydrogen and air (*22*)



It has been shown that hydrogen exposure can reduce ductility in API 5L steels. Hoschke *et al.* conducted a detailed review and summarized studies investigating the effect of hydrogen on tensile properties of pipeline steels (*23*). Results of dynamic slow strain rate tensile tests indicate that in a hydrogen environment, various steel grades display different levels of vulnerability to hydrogen embrittlement, typically increasing with an increase in the steel strength rating (*24*). Myhre *et al.* evaluated tensile properties of three vintage and one modern X65 and X70 pipeline steels, through slow strain rate tensile testing (*25*). Their work revealed that all the tested materials exhibited reduction in ductility under hydrogen exposure. Nguyen *et al.* evaluated the impact of hydrogen at different concentrations in methane on the tensile properties of X42, X65, X70 steels (*26*). The results of slow strain tensile tests on the three different grades of API 5L steel are shown in Figure 7. All three steels show a greater reduction in ultimate tensile strength under tests with pure hydrogen, compared to tests with lower concentration of hydrogen in methane. All three steel grades demonstrate some reduction in ultimate tensile strength during tests in 30% hydrogen in methane, with X65 steel exhibiting most significant reduction. The tests conducted under 1% hydrogen in methane environment demonstrate only minor reduction of ultimate tensile strength in X42 steel, while the other two steel grades do not show changes relative to tests conducted in ambient air.

Figure 7: Stress-strain curves under different environment conditions for (a) X42, (b) X65, and (c) X70 (*26*)



Multiple recent studies have investigated the effects of hydrogen on API 5L X80 steels, more specifically hydrogen embrittlement, since X80 is a high strength steel grade commonly used in high pressure gas transmission pipelines and it is believed to be affected to a greater extent by hydrogen embrittlement compared to lower strength steels (*27–35*). The findings from these studies suggest that existing defects play a significant role in hydrogen embrittlement. Gas impurities such as carbon monoxide (CO) have inhibitive properties, and crack growth rate increases and ductility reduces with the increasing hydrogen partial pressure. Particular emphasis has been placed on investigating the impacts of hydrogen on welds and the associated heat-affected zones in X80 steels (*27*, *30*, *34*, *35*), since welds in gas pipelines are considered points of potential vulnerability and potentially have greater susceptibility to hydrogen embrittlement (*36*). These studies primarily focus on investigating the role of defects in hydrogen embrittlement. The effect on mechanical characteristics of X52 and X65 steels under exposure to hydrogen has also been the subject of recent research (*37–42*).

The studies involving API 5L listed above were conducted under different experimental settings and employed test samples from various origins and conditions, which makes direct comparison of these findings or drawing any general conclusions challenging (*43*). Although these studies provide valuable insights into impacts of hydrogen on steels, direct implications from these studies have limitations. Jia *et al.* suggest that different natural gas network systems could tolerate different hydrogen concentrations, and a precise evaluation that takes into account the particular circumstances of each system must be undertaken (*44*).

The guiding standard which defines requirements and specifications for design, fabrication, installation, and inspection of "Hydrogen Piping and Pipelines" is ASME B31.12, published and periodically updated by the American Society of Mechanical Engineers (ASME). The previous version of the standard (B31.12-2019) specified a minimum of 10% hydrogen by volume, leaving hydrogen blending below 10% under the ASME B31.8 standard (*45*). The current edition of ASME B31.12-2023 no longer has a minimum requirement of 10% hydrogen for applicability, however it excludes "pipeline systems designed to ASME B31.8 with hydrogen-containing gas mixtures that have been demonstrated by engineering analysis or successful experience to not adversely affect the integrity of the pipeline systems". Furthermore, ASME B31.12-2023 Code Case 220 implements improved fatigue design curves (sensitive to pressure and load ratio) for pipeline steels used with gaseous hydrogen at partial pressure of 20 MPa (2901 psi) or less (*46*).

It has been suggested that recommendations given by ASME B31.12 are based on the effect of hydrogen at pressures and concentrations greater than those that are usual for transmission or distribution pipeline systems (*47*). Ott *et al.* examined applicability of ASME B31.8 and ASME B31.12 standards to hydrogen blended natural gas service and suggested a strategy for identifying compliance gaps and correcting shortcomings (*48*).

Despite the generally unfavorable effects of hydrogen on mechanical properties of carbon steels, multiple studies have performed testing outlined by ASME B31.12 to demonstrate suitability of API 5L grade steel pipes with hydrogen gas. Martin *et al.* demonstrated through laboratory testing that X70 pipe steel designed for natural gas service can be used in hydrogen blended service despite an observed discernible decrease in fracture toughness (*49*). Project SyWest H2 examined European natural gas pipelines according to ASME B31.12 standard to assess their compatibility with hydrogen (*50*). Fracture mechanics studies on crack growth and fracture toughness conducted during the project concluded that "all pipeline steel grades tested are essentially suitable for hydrogen transport" (*50*). Olsen *et al.* established methodologies for conversion of natural gas pipelines for hydrogen service, in accordance to ASME

B31.8 and ASME B31.12 codes (*51*). Esmaeely *et al.* provide a list of technical aspects to be evaluated prior to introducing hydrogen in existing natural gas infrastructure network (*52*). Sanchez-Lainez *et al.* observed that X42, X52, X60, X70 steels subjected to exposure of 20% hydrogen in methane at 80 bar (1160 psi) for 3000 hours, as part of a demonstration project, did not suffer embrittlement or other type of damage (*53*). Material testing work conducted as part of the research efforts of the demonstration project FutureGrid, aiming to evaluate fitness of the existing natural gas infrastructure in Great Britain with various concentrations of blended hydrogen, included testing of X52, X60, and X70 steels in accordance to ASME B31.12 (*54*). The testing results qualified the tested materials for service with 100% hydrogen at pressures up to 106.5 bar (1545 psi).

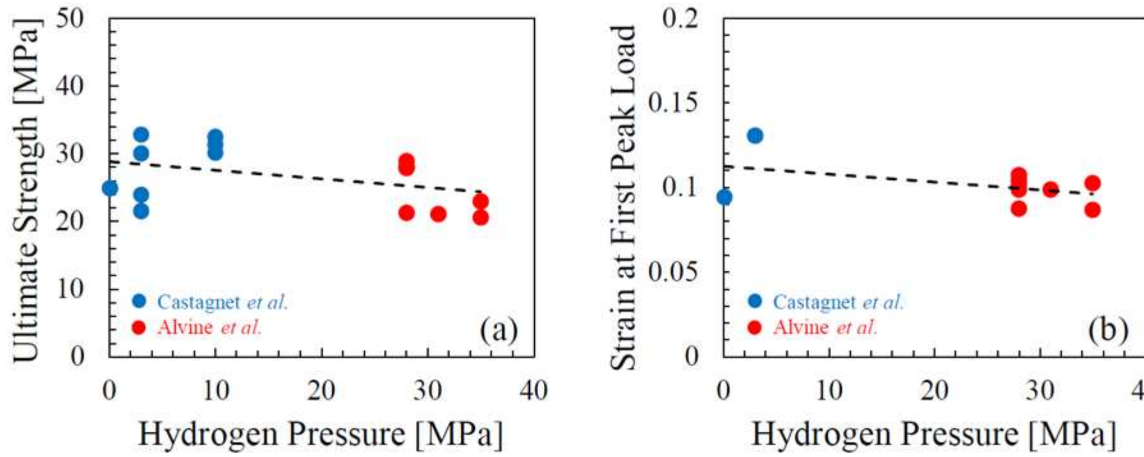
Pipeline plastics

Polyethylene (PE), polyvinyl chloride (PVC), and acrylonitrile butadiene styrene (ABS) thermoplastic materials are commonly used in natural gas distribution pipelines, which usually operate at pressures of 1.4 MPa (203 psi) or lower (*5*). In addition to these three, polyamide (PA) has been recently approved for use in natural gas distribution network by 49 CFR Part 192 (*4*). Of these materials, PE is the most widely used polymer material in the natural gas distribution network (*6*).

One common method used to investigate the effects of hydrogen on PE is uniaxial tensile testing (*55*). At low pressures, quasi-static tensile testing shows no significant impact from hydrogen on mechanical properties of PE; nevertheless, at higher pressures, tensile strength is somewhat reduced (*3*). Simmons *et al.* suggest that the relatively small reported reduction of yield strength and the strain at the first peak load[6] at high pressures seen in Figure 8 may be the result of exposure to high pressure and independent of the gas present (*55*).

[6] The maximum load a material specimen can withstand before failure.

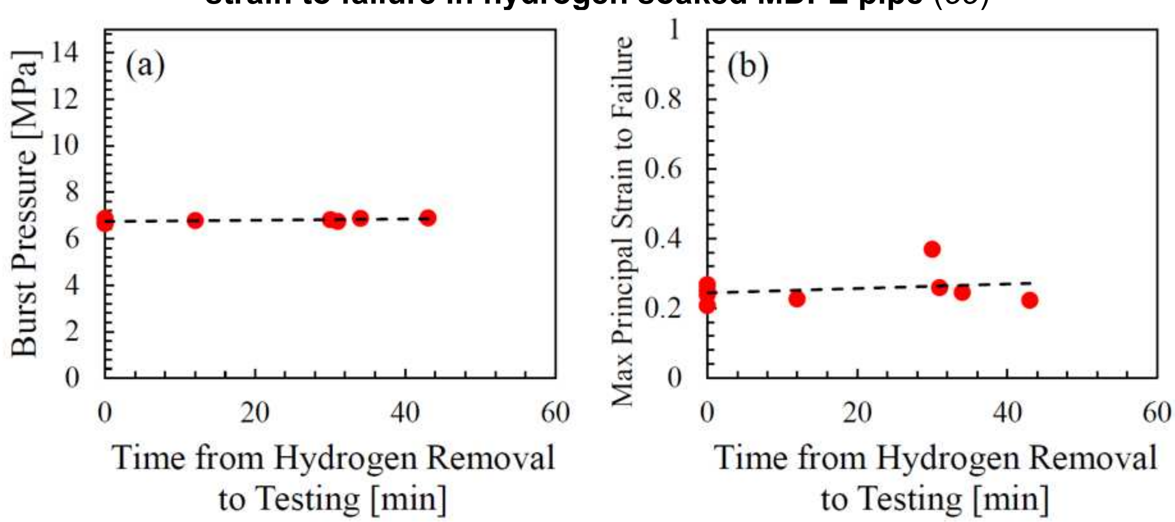
Figure 8: Effect of hydrogen pressure on the uniaxial tensile properties of HDPE, (a) ultimate strength (b) strain at the first peak load (*55*)



Studies on the effects of hydrogen on the fracture properties of high density polyethylene (HDPE) through quasi-static *in situ* tests on notch test samples performed at room temperature observed no noticeable effects from hydrogen (*55*).

Simmons *et al.* performed burst tests on medium density polyethylene (MDPE) pipes after exposure to pure hydrogen environment for 72 hours (*55*). After pipes were removed from hydrogen exposure, the hydrogen diffused out of the MDPE material, and only 40% of the original amount was present in the material after 40 min following removal. Figure 9 (a) shows the effect of time duration after removal on burst pressure, while Figure 9 (b) shows the effect on maximum principal strain to failure. Both parameters appear relatively unchanged from 0 to 45 min after removal from hydrogen environment, suggesting no significant effect of hydrogen on burst failure.

Figure 9: Effect of interval time on (a) burst pressure and (b) maximum principal strain to failure in hydrogen soaked MDPE pipe (*55*)



Simmons *et al.* evaluated hardness and elastic modulus[7] of MDPE pipe after they performed nanoindentation on the cross section of the pipe wall (*55*). Nanoindentation was performed in three groups of samples: immediately after exposure to hydrogen at 250 psi for 72 hours on the first group of samples, 14 days after removal from hydrogen exposure for 72 hours on the second group of samples, and after no exposure to hydrogen on the third group of samples. Reduction in both hardness and elastic modulus was observed only in the samples on which nanoindentation was performed immediately after hydrogen exposure (54)(54).

Shrestha *et al.* evaluated fatigue life and fracture resistance of MDPE pipe exposed to high pressure hydrogen (*56*). Their results demonstrated that hydrogen did not affect fatigue life and fracture resistance of the tested MDPE material.

Little research has been published on the impacts of hydrogen on ABS, PVC and PA materials. However, according to PPI TR 19-2020 (Plastics Pipe Institute Technical Report), PVC is resistant to hydrogen gas up to 140 °F, while PA11 and PA12 are resistant to hydrogen gas up to 194 °F (*4*).

Pipeline gaskets and seals

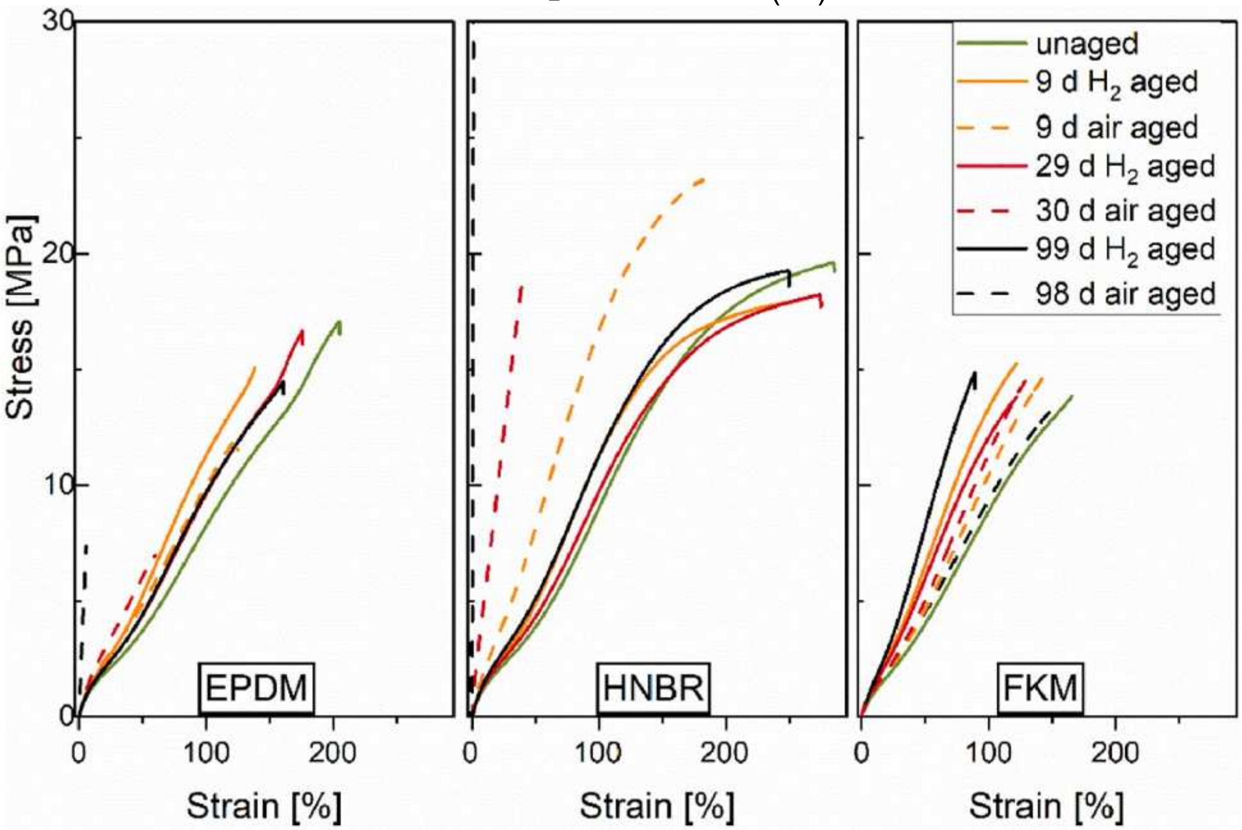
Materials used in seals predominantly include elastomers and semicrystalline thermoplastics. Nitrile rubber (NBR), using the trade name of Buna N, fluoroelastomers of vinylidene fluoride (FKM), using tradename Viton, and polytetrafluoroethylene (PTFE), with tradename Teflon, are used in gasket and o-ring seals in flange pipe connections (*6*). Other sealing materials used in valves and regulators include ethylenepropylene (EPDM), hydrogenated nitrile rubber (HNBR), polychloroprene (CR), polyamide (*57*).

Zaghdoudi *et al.* investigated the effects of hydrogen on EPDM, HNBR and FKM and compare them to thermo-oxidative aging, by subjecting them to aging in hydrogen and air environments, at a temperature of 150 °C (302°F) and pressure of 50 bar (725 psi), for different time duration ranging from 9 to 100 days (*58*). Testing included measurements of density, hardness, tensile properties and hydrogen permeability. Hardness of all three elastomers was not affected by hydrogen aging. Similarly, hydrogen did not impact the density of these elastomers. In terms of permeability of hydrogen, no change was observed after aging in hydrogen. Figure 10 shows stress-strain curves from tensile tests on the three elastomers, for unaged samples and sample aged in air and in hydrogen. EPDM and HNBR samples aged in air show a reduction in ductility, while the samples aged in hydrogen are not significantly impacted

[7] A measure of stiffness in uniaxial tension or compression test.

compared to unaged samples (green solid lines). On the other hand, FKM samples aged in hydrogen exhibit greater reduction in ductility compared to sample aged in air and the unaged sample.

Figure 10: Tensile test results of (a) EPDM, (b) HNBR, and (c) FKM aged in air and in H_2 environment (*58*)



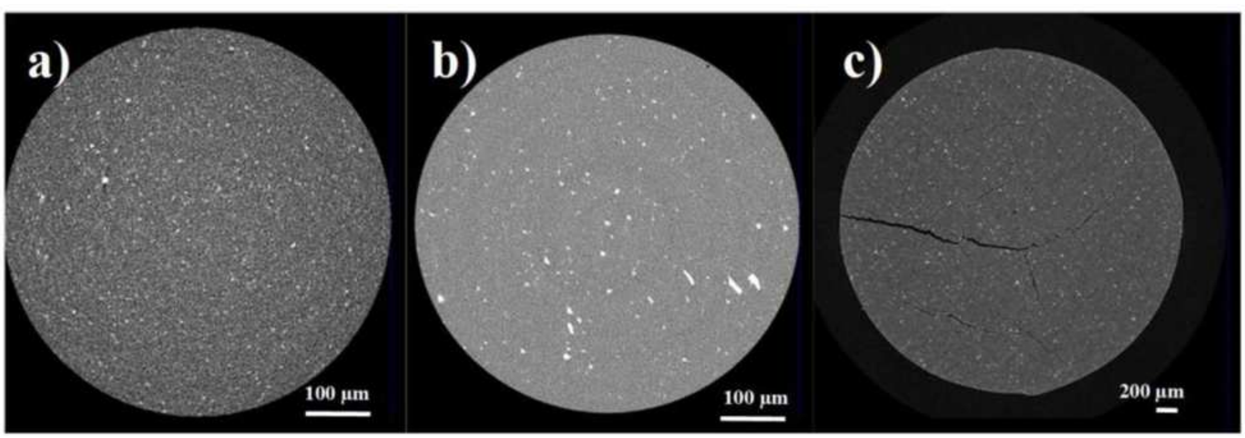
The solubility of hydrogen in the bulk polymer material can cause swelling in elastomers, leading to change in dimensions of seals and gaskets, and deformation which could impair their function (*4*, *57*). Nitrile (NBR) and Viton (FKM) samples were subjected to hydrogen gas at a pressure of 103 MPa (14,939 psi) for a week at Sandia National Laboratory, and then they were rapidly depressurized at a rate of 125 psi/sec (*57*). The results of the study are summarized in Table 2. All Buna A (NBR) and Viton (FKM) components subjected to 100% hydrogen exhibit signs of swelling upon examination immediately after removal from the high-pressure hydrogen environment. The expansion in Viton A gasket is the largest, resulting in more than doubling of its original size. The swelling effect appears reversible, since after 48 hours after removal from high-pressure hydrogen environment most components return to their original dimensions.

Table 2: Change in volume of elastomer materials after exposure to hydrogen at high pressure (*57*)

Polymer	**% change in volume per gram upon hydrogen exposure**	
	Immediately after removal	**48 hours after removal**
Buna N sheet	57.2	3.9
Buna N 'o' ring	22.6	0.2
Viton A sheet	69.0	11.5
Viton A 'o' ring	37.1	0.8
Viton gasket	114.3	7.9

Further testing conducted by Sandia National Laboratory included X-ray Tomography of EPDM, NBR, and FKM samples subjected to hydrogen at 90 MPa (13053 psi) (*57*). The respective images shown in Figure 11 show formation of voids in all three materials, which was evident even after swelling of these materials had reduced. A crack is visible in Viton A material, as shown in Figure 11 (c).

Figure 11: X-ray computed tomography images of (a) EPDM, (b) NBR, and (c) FKM (Viton A) after exposure to hydrogen at high pressure (*57*)



Other investigated materials, such as PTFE (Teflon) and EPDM, demonstrated negligible to no swelling effects during high-pressure hydrogen exposure (*4*). It should be noted that the hydrogen pressures of 103 MPa (14939 psi) and 90 MPa (13053 psi) these elastomer materials were subjected to are significantly higher (up to 10 times) than the typical operating pressures of transmission pipelines.

In addition to swelling, hydrogen diffusion in elastomers subjected to high-pressure hydrogen can lead to rapid gas decompression failure upon sudden reduction in pressure (*59*). This can cause blistering, splits, and crack defects in elastomers.

The H2SAREA project assessed the operation of a test gas line loop representative of the natural gas distribution system in Spain, under a natural gas blend containing 20% hydrogen (*60*). Rubber seals were tested in a 100% hydrogen environment at 16 bar (232 psi) pressure, which led to degradation of NBR seals. Blistering on the surface of NBR seal was observed and is shown in Figure 12.

Figure 12: Blistering on seal, observed in (a) immediate inspection, (b) immediate inspection (perspective), (c) after 24 hours with no signs of blistering (*60*)

Impacts on meters, pressure regulators, and valves

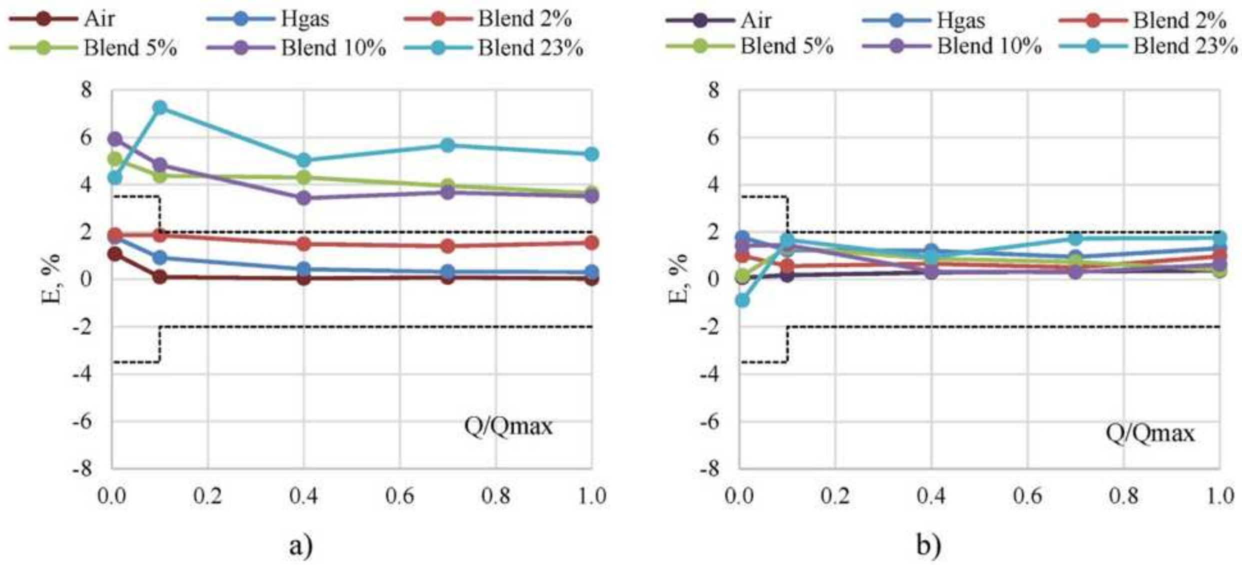
Since valve bodies are often made of steel, and components inside valves (e.g. o-rings, seats, gaskets, seals) employ polymer materials (*4*), valves are at potential risk to suffer some of the detrimental effects of hydrogen discussed in the previous sections. One primary area of concern is gas leak from valves (*6*). To that end, several demonstration projects have evaluated components including valves that are commonly used in natural gas systems with hydrogen blended in natural gas at various concentrations. More details on these projects are provided in Chapter 2.

Information about how hydrogen blending in natural gas and the concentrations affect the performance and integrity of pressure regulators and reducers is scarce (*3*). Part of the research efforts undertaken by the HyDelta project in the Netherlands, aimed at identifying and reducing barriers to utilizing existing natural gas network with pure hydrogen, included experimental performance evaluation of 40 domestic pressure regulators with pure hydrogen at inlet pressures of 37.5 mbar (0.544 psi) and 100 mbar (1.45 psi) (*61*). The study revealed that the shut-off pressure on valves after regulators was several mbar (several hundredths of a psi) greater with hydrogen than with natural gas.

(*4*)Commonly used natural gas flow meters in the transmission and distribution system include turbine, ultrasonic, rotary, and diaphragm meters (*62*). Most common natural gas meter types used in residential and small commercial and industrial applications include diaphragm, ultrasonic, and thermal mass meters (*63*). Most natural gas meters are susceptible to measurement error when used with hydrogen blended natural gas due to the differences in thermophysical properties of the gas blend compared to natural gas. This error depends on the measurement mechanism used by a specific gas meter type and concentration of hydrogen in natural gas. Some meters can use correction factors to compensate for this error in situations where the exact composition of the gas blend is known and does not change over time (*3*).

Due to their principles of operation, measurement accuracy of ultrasonic and diaphragm gas meters is less affected by hydrogen blending with natural gas (*64*). Ficco *et al.* compared measurement accuracy of different domestic natural gas meters with air, natural gas, and gas blends of hydrogen and natural gas, with hydrogen concentrations of 2%, 5%, 10%, and 23% (*64*). The meter selection included one diaphragm, two ultrasonic, and two thermal mass meters. Measurement error of diaphragm meter with hydrogen containing gas blends was comparable to natural gas and air. Larger measurement error was observed for very small flow rates; however, it was still within the allowable error limits. The results from the tests performed on two ultrasonic gas meters and a second generation thermal mass gas meter, which is listed as "hydrogen ready", also demonstrated errors within the allowed limit range for all test gas blends. However, the first generation thermal mass meter exhibits errors above the allowed limit range, as demonstrated in Figure 13 (a), which are above permissible error limits for hydrogen blending concentration of 5%, 10%, and 23% in natural gas, over the maximum flow range of the gas meter (Q_{MAX}). Measurement error increases with increase in hydrogen concentration in the blend.

Figure 13**: Measurement error of the thermal mass meters, (a) first generation, (b) second generation ("hydrogen ready")** (*64*)



Testing conducted under project NewGasMet included testing of a rotary flow gas meter with air, natural gas, and hydrogen enriched natural gas (HENG), at concentrations of up to 15% hydrogen, at pressures of 9 bar (131 psi) and 16 bar (232 psi) (*65*). Figure 14 reveals the measurement error for all test conditions, suggesting that the error difference between natural gas and 15% hydrogen blended natural gas is insignificant.

The NewGasMet project also tested six diaphragm gas meters from two different manufactures, with air, nitrogen, methane, hydrogen, and hydrogen blended in methane at concentrations of 20% and 30% (*66*). The diaphragm gas meters were calibrated with nitrogen and hydrogen at three different flow rates at atmospheric pressure and ambient temperature. Figure 15 shows measurement error from two of the tested diaphragm meters. The study concluded that the measurement error for hydrogen blends in methane in all diaphragm meters, was similar to that for air, nitrogen, and methane. There was no systematic difference in measurement error with a specific gas being measured.

Figure 14: Rotary flow meter error for different gases and pressures (*65*)

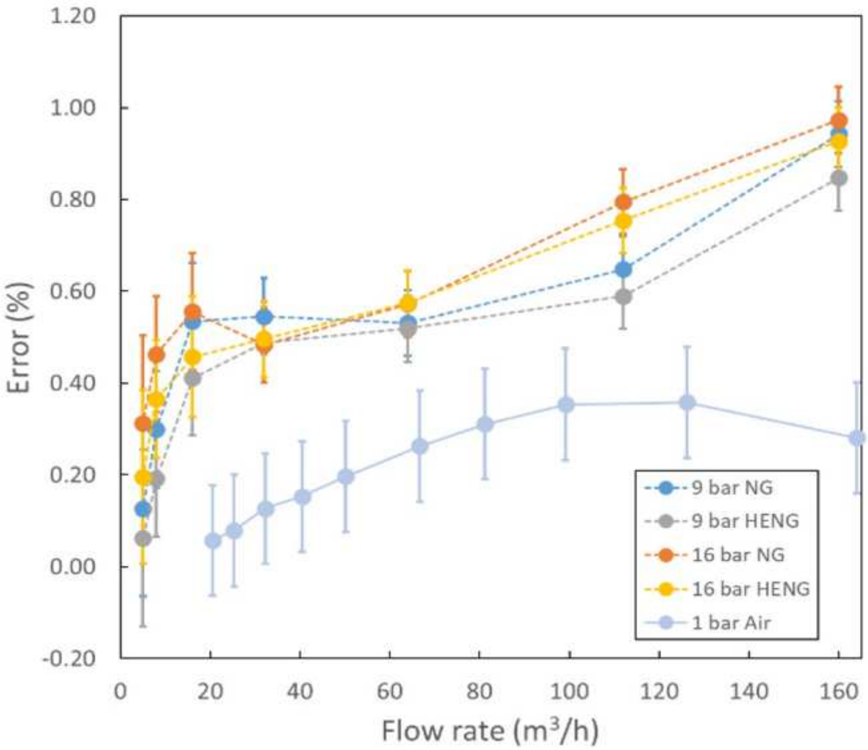
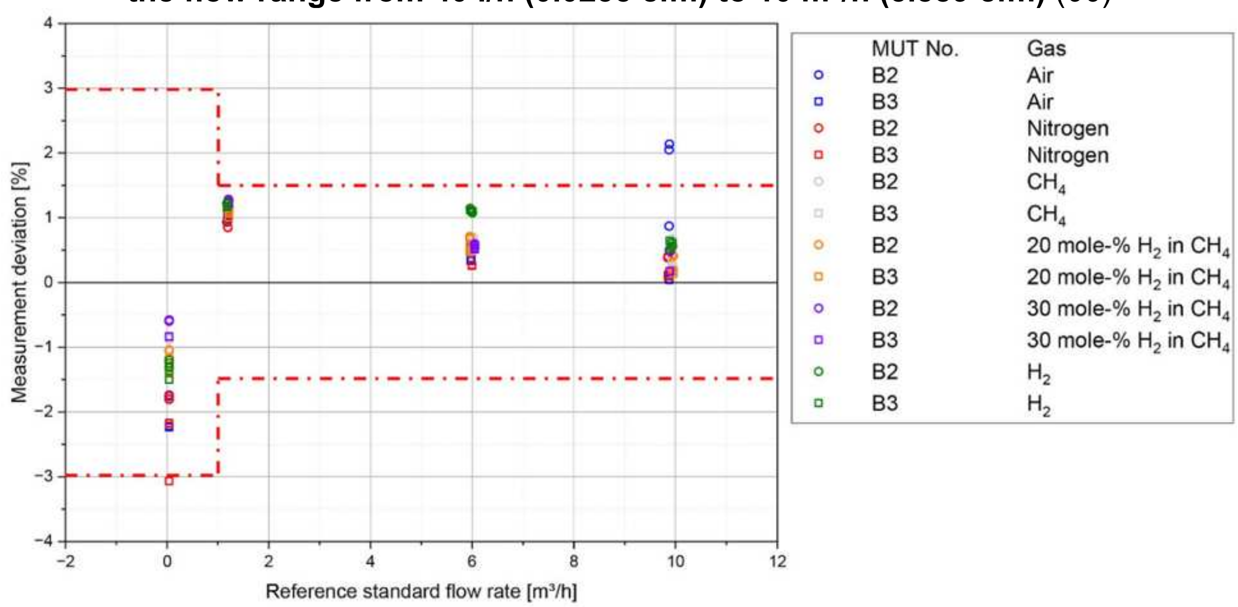


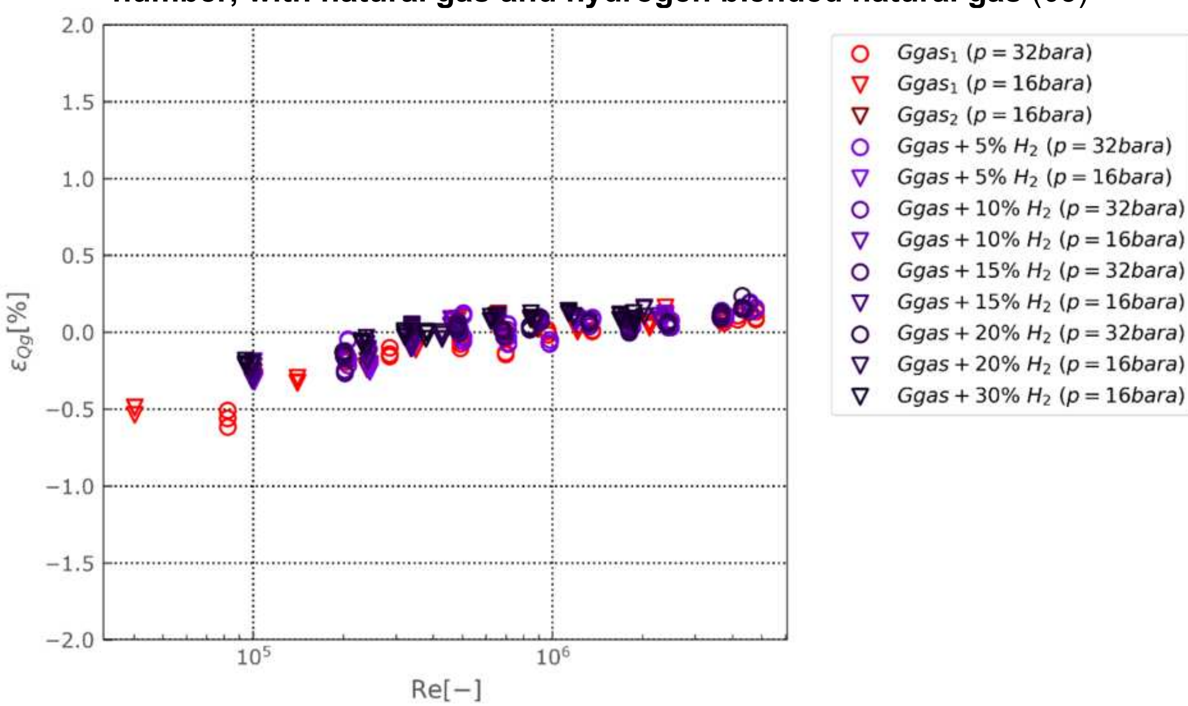
Figure 15: Gas type-dependent measurement deviation from diaphragm meter in the flow range from 40 l/h (0.0235 cfm) to 10 m^3/h (5.889 cfm) (*66*)



Testing conducted by DNV (Det Norske Veritas) on turbine, ultrasonic, and Coriolis gas meters with natural gas and hydrogen blended natural gas with concentrations of 5%, 10%, 15%, 20%, and 30%, at pressures of 16 bar (232 psi) and 32 bar (464 psi), demonstrated measurement errors of 1% or lower for all gas blends (*63*). It should be noted that corrections for pressure and speed of sound for the different test gases measured by Coriolis meter were applied. Figure 16 shows the results from tests on a 6-inch turbine gas meter. The results suggest no systematic trend in measurement error with the concentration of hydrogen blended in natural gas.

With respect to durability of common natural gas meters with hydrogen, one study observed no impact to materials of ultrasonic, diaphragm, and turbine gas meters with up to 30% hydrogen blended in natural gas (*64*). Project NewGasMet investigated the effect of hydrogen on diaphragm and thermal mass flow meters by exposing them to static hydrogen for 6 or 12 months (*67*). The study did not report any impacts on the materials used in the construction of the tested gas meters.

Figure 16: Measurement error of 6-inch turbine meter as a function of Reynolds number, with natural gas and hydrogen blended natural gas (*63*)



Another operational difference deserving consideration in valves is different changes in temperatures due to the different Joule-Thompson coefficients[8] (JTC) of natural gas and hydrogen, as demonstrated by modeling work (*68*), since hydrogen has a negative JTC and methane has a positive JTC. The positive JTC of methane gas indicates that

[8] A metric for the change in temperature of a gas upon pressure reduction, assuming no exchange of heat with its surroundings.

the gas temperature will decrease while undergoing a pressure reduction through the valve, while the negative JTC of hydrogen gas indicates that the gas temperature will increase while undergoing a pressure reduction through the valve. Zhang *et al.* demonstrated through a computational fluid dynamics (CFD) model that JTC for gas flow inside a valve decreases by about 30% and 50%, at hydrogen concentrations in natural gas of 15% and 30%, respectively (*69*). The reduced JTC would result in a reduction in temperature drop in the valve.

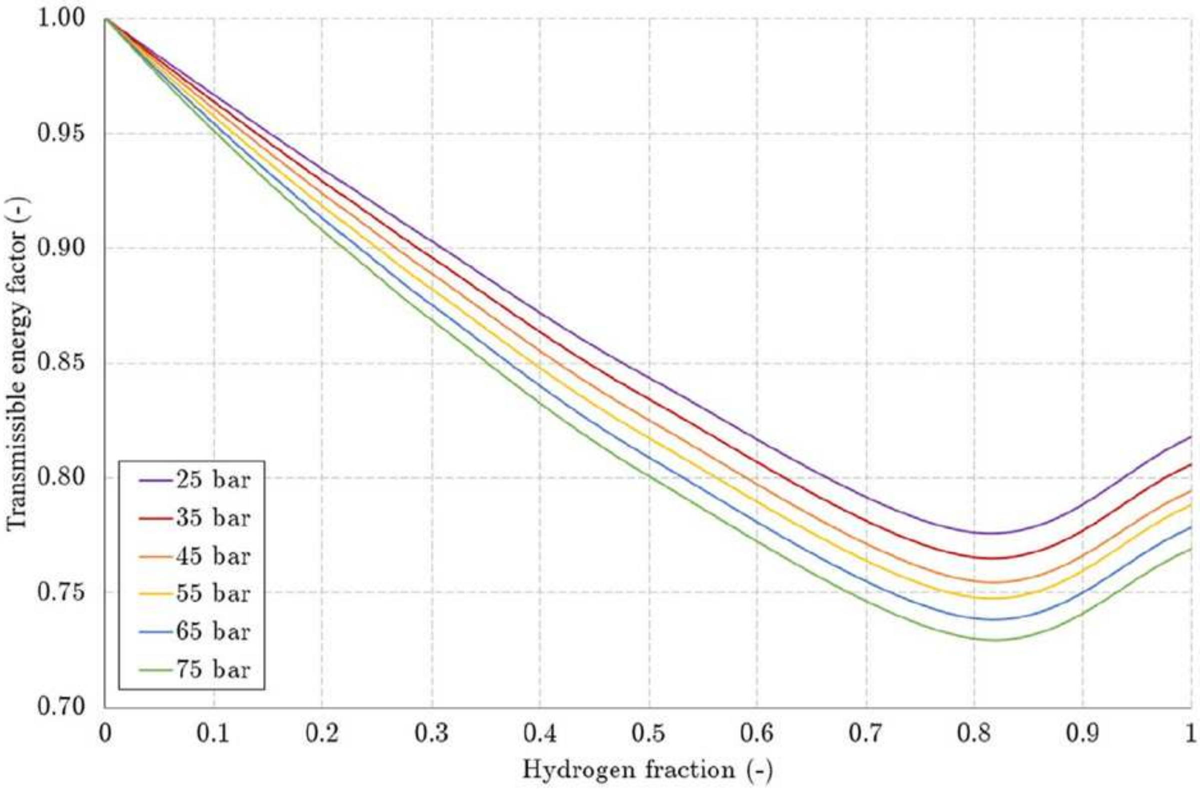
Other considerations with the use of natural gas regulators with hydrogen include hydrogen compatibility with materials used in regulators and changes in temperature due to change in JTC with hydrogen blending. In particular, when used with hydrogen blends, regulators made of metals susceptible to hydrogen driven phenomena must be assessed carefully according to operational circumstances (*4*).

Impacts on gas compression and transport

Hydrogen gas has approximately one third the energy content of typical natural gas on a volumetric basis, which raises questions about the ability of existing natural gas infrastructure to store and transport the same amount of energy when hydrogen is blended with natural gas (*70*). The increase in volumetric gas flow rate of hydrogen blended natural gas can partly compensate for its lower energy density, but not entirely. Numerical investigations have shown that if gas pipeline pressure conditions are kept constant for methane blends containing 10% hydrogen, the gas flow rate increases by 4%, whereas with 20% hydrogen content gas flow rate increases by 9% (*71*). Galyas *et al.* evaluated the energy transmissibility in a modeled transmission pipeline of hydrogen-methane blends, with hydrogen concentrations from 0% to 100% (*71*). Transmissibility energy factor of gas blend, defined as the ratio of transmitted energy content of hydrogen-methane blend to that of pure methane, is shown in Figure 17, under a pressure range of 25 bar (363 psi) to 75 bar (1088 psi) and a fixed temperature of 10 °C (50 °F). As hydrogen content in methane increases from 0% to a little over 80%, the transmissibility energy factor decreases from 1 to roughly 0.75. The shape of transmissibility energy factor curves in Figure 17 is influenced by the heating value of the gas mixture, which decreases linearly as hydrogen concentration in methane increases from 0% to 100%. However, another influencing factor on the shape of the curves is throughput capacity of the pipeline. The throughput capacity is dependent upon the square root of the density of the gas mixture, which changes non-linearly with increasing concentration of hydrogen blended in methane.

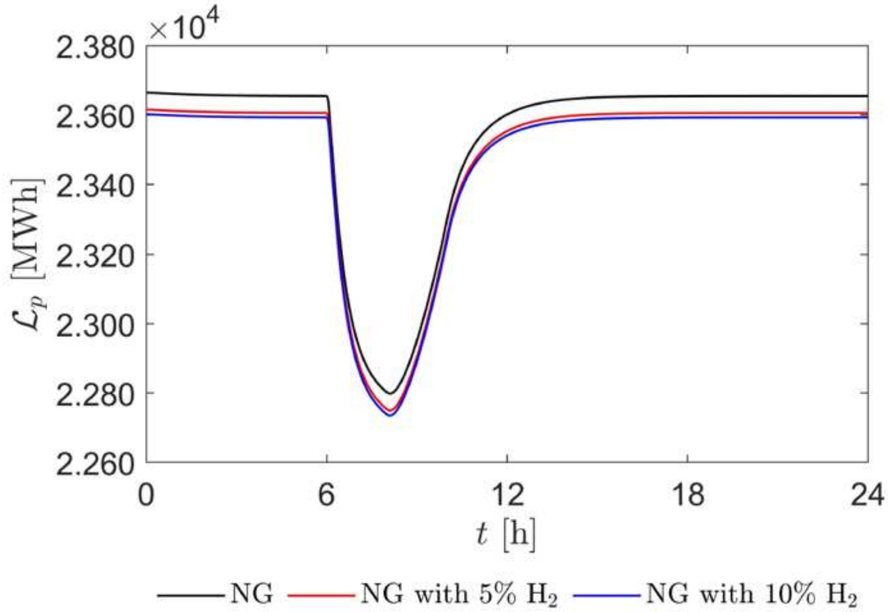
This suggests that in order to maintain the same energy transmission capacity with hydrogen-natural gas mixtures, operating pressures need to be increased to achieve higher gas flow rates (*72–74*). Tan *et al.* employed computational fluid dynamics (CFD) modeling to demonstrate that the increase in energy necessary to maintain constant energy transmission capacity with hydrogen blended natural gas greatly depends on pipeline surface roughness and pipeline inner diameter, which determines the pipeline inner surface to volume ratio (*75*).

Figure 17: Transmissibility factor for hydrogen-methane blends at different pressures and 10 ˚C (50 ˚F) temperature (*71*)



Another consequence of hydrogen's lower energy density in comparison to natural gas is the reduction of linepack, which is defined as the amount of energy stored in pipelines (*76*). Simulation results for linepack in gas transmission pipeline with natural gas and hydrogen blended natural gas at concentrations of 5% and 10% are shown in Figure 18, where L_P represents the linepack in MWh (3.41×10^6 BTU) as a function of pressure (*77*). A small but noticeable reduction in linepack is observed with the blends containing hydrogen in comparison to natural gas alone. The overall shape of the curves in Figure 18 is characterized by compressor operation and resulting change in pressure.

Figure 18: Simulated linepack for natural gas hydrogen blended natural gas at 5% and 10% (*77*)



Increase in compression power necessary to maintain a constant energy flow after the addition of hydrogen to natural gas has significant implications to compression stations and compressor operation (*3*). Peng *et al.* used numerical modeling to investigate performance of centrifugal compressors in transmission pipeline with various concentrations of hydrogen blended in natural gas (*78*). The results revealed a downward shift of the centrifugal compressor performance curve with the addition of hydrogen. Liu *et al.* employed a model to study the effects of hydrogen blending at 5%, 10%, 15%, and 20% on the performance and efficiency of different type of compressors (*79*). The study revealed that the efficiency of fuel-driven compressors, and the efficiency of electrically driven compressors, and the average efficiency of compressor units decreases with increasing concentrations of hydrogen blended in natural gas. Modorskii and Cherepanov investigated the effect of hydrogen blending on vibration in compressors through a numerical simulation, and revealed that the addition on hydrogen reduces oscillatory amplitude (*80*).

Because compressor construction includes a variety of metals, including high strength steels and polymers used in seals, they deserve careful assessment, due to the negative impact of hydrogen on mechanical properties of some of the employed materials (*70*). The demand for increased operating pressures with hydrogen blending could further intensify these risks and trigger modifications or replacements of existing compressors (*3*).

Hydrogen blending pilot projects

Several pilot projects on blending hydrogen into existing natural gas distribution network systems have been announced in recent years in different countries. The hydrogen blended natural gas delivered to end-users as part of these projects often has a target hydrogen concentration of 2% to 20% by volume. Some of the pilot studies have been completed and findings and outcomes have been published.

The Jupiter 1000 project led by GRTgaz, which was commissioned in 2019 in southern France, achieved megawatt scale generation of hydrogen through electrolysis, and subsequent blending and distribution of hydrogen of up to 2% in natural gas to several industrial customers (*81*). The German Association for Gas and Water, DVGW, conducted the H2-20 pilot project, which demonstrated injection of 10%, 15%, and 20% hydrogen into a distribution natural gas network that delivered gas to about 350 domestic and commercial customers in the Fläming region located in Saxony-Anhalt (*82*). During the demonstration 300 extensive spot checks were performed and no hydrogen related safety issues were identified.

The HyDeploy 2 project in Great Britain demonstrated the blending of 20% hydrogen in a small portion of the natural gas distribution system located at the village of Winlaton (*83*). The gas pipe network of Winlaton consisted primarily of polyethylene, cast iron, and steel pipes. All appliances on the Winlaton trial network functioned as intended, with no appliance malfunctions brought on by the use of hydrogen blended gas. It was reported that one 4-inch spun cast iron main, part of a 600 meter long cast iron section on the network, experienced a fracture during the demonstration. Since failures of this nature are not uncommon, it could not be definitely connected to hydrogen blending. Frequent gas leak checks performed throughout the demonstration period did not identify an increase in the number of leaks.

The Hydrogen Park South Australia project in Australia accomplished blending of 5% renewable hydrogen in the natural gas network serving 4000 homes and businesses in metropolitan Adelaide (*84*). The project findings revealed that 5% hydrogen blending had little effect on odorant levels, and blended gas composition was quite constant at different sites downstream of injection. Furthermore, no leaks have been found in the gas network during surveys conducted before, at the start of blending, and after a year of operation. Lastly, 90 homes had their appliances inspected, and most of them were deemed to be in good operating order.

In another pilot project in Australia, ATCO Gas and Pipelines Ltd (ATCO) demonstrated injection of 2% renewable hydrogen and delivery to 2700 residential and commercial gas customers located in Glen Iris, Calleya and Treeby (*85*). Concentration of hydrogen blended in the natural gas network is expected to increase to 10% in future stages of the project.

ATCO in Canada started supplying about 2,100 customers with a 5% hydrogen blend in natural gas in 2022 using a portion of the current Fort Saskatchewan natural gas distribution system (*86*, *87*). In order to understand potential hazards related to the introduction of blended gas into its current distribution system and to its customers, ATCO conducted quantitative risk assessments. The assessment revealed that for all operating pressures and blend cases taken into consideration for the project, adding hydrogen raises the individual risk (IR)[9] level of ignited releases from mains, services, meters, regulators, and end user appliances. However, IR was consistently well below the generally accepted reference criteria of 10^{-6} per year. The IR component associated with carbon monoxide poisoning decreased with the addition of hydrogen blended in natural gas.

Another pilot project in Canada by Enbridge Gas Inc. is currently serving approximately 3,600 residential customers with a 2% hydrogen blended natural gas using the distribution network located in Markham, Ontario (*88*).

[9] A measure of probability of harm to a person present in a specific location, due to an accidental fire.

CHAPTER 2: Leakage rates of hydrogen blends

Leakage rates of hydrogen and natural gas blends from the natural gas infrastructure is an important topic due to hydrogen's fire hazard risks and its indirect global warming potential. This chapter covers recent findings on this topic. The type of leaks covered are of pneumatic nature, which are defined as gas leaks that occur through a physical aperture under pressure gradient. Permeation leaks through polymers and other materials, which are typically several orders of magnitude lower, are discussed in Chapter 3. Gas release, dispersion, and associated fire hazard safety risks are also discussed in this chapter.

Comparison of leak rates of hydrogen and hydrogen blends to pure methane or natural gas

Over the past years, several large demonstration projects have investigated the leak rates of hydrogen-methane gas blends or pure hydrogen in comparison to leak rates of pure methane (*54*, *60*, *84*, *89–91*). These studies have primarily focused on the natural gas distribution system, including piping, meters, valves, fittings, and end-use equipment.

The European project Testing Hydrogen admixture for Gas Applications (ThyGA), which evaluated feasibility of conversion of natural gas distribution network to hydrogen and its impact on appliances, conducted an investigation of leaks from components on domestic and commercial gas lines, located between gas meters and end user appliances (*89*). The testing was performed at a gas line pressure of 35 mbar (0.508 psi), with helium, air, and a gas blend of 40% hydrogen and 60% methane. The tested natural gas line components were obtained from installations used in Germany, Denmark, Belgium, and France. Ten test lines were constructed using these components, which were then subjected to short-term leak tests lasting several minutes, and long-term tests lasting minimum 10 days. Leak flow rate was assessed based on pressure drop in the line over time. The results of the short-term tests with a gas blend of 40% hydrogen and 60% methane are shown in Table 3. While these flow rates are well below the admissible leak rate of 0.1 l/h (3.53×10^{-3} cfm) used by the study, the authors indicate that leak rates between the blend of 40% hydrogen and 60% methane and helium and air are indistinguishable. Furthermore, some of the leak rates are negative, for which no physical explanation could be provided. These results can potentially be attributed to uncertainty in measurement.

Table 3: Short-term leak rates of 40% H2 and 60% CH_4 gas blend for 10 lines (*89*)

Line number	Line volume	P1	P2	T1	T2	ΔP, mbar	n_{leak}	Leakage flow
	liter	*bar*	*bar*	*°C*	*°C*	*mbar*	*mole,* × 10^{-6}	*$l.h^{-1}$,* × 10^{-4}
1	0.18	-	-	-	-	-	**-**	-
2	1.15	-	-	-	-	-	**-**	-
3	3.32	1.032	1.032	21.32	21.32	-0.05	**-7.34**	**-9.86**
4	0.46	1.033	1.033	21.00	20.96	-0.45	**-8.44**	**-11.34**
5	10.58	1.033	1.033	21.43	21.45	-0.04	**-17.90**	**-24.05**
6	8.24	1.033	1.033	21.51	21.59	0.25	**82.96**	**111.50**
7	0.22	1.033	1.033	21.44	21.57	0.35	**3.16**	**4.24**
8	0.74	1.034	1.033	21.05	21.01	0.06	**1.93**	**2.59**
9	0.35	1.030	1.030	21.22	21.11	-0.19	**-2.83**	**-3.80**
10	0.42	1.030	1.030	21.35	21.48	0.48	**8.36**	**11.24**

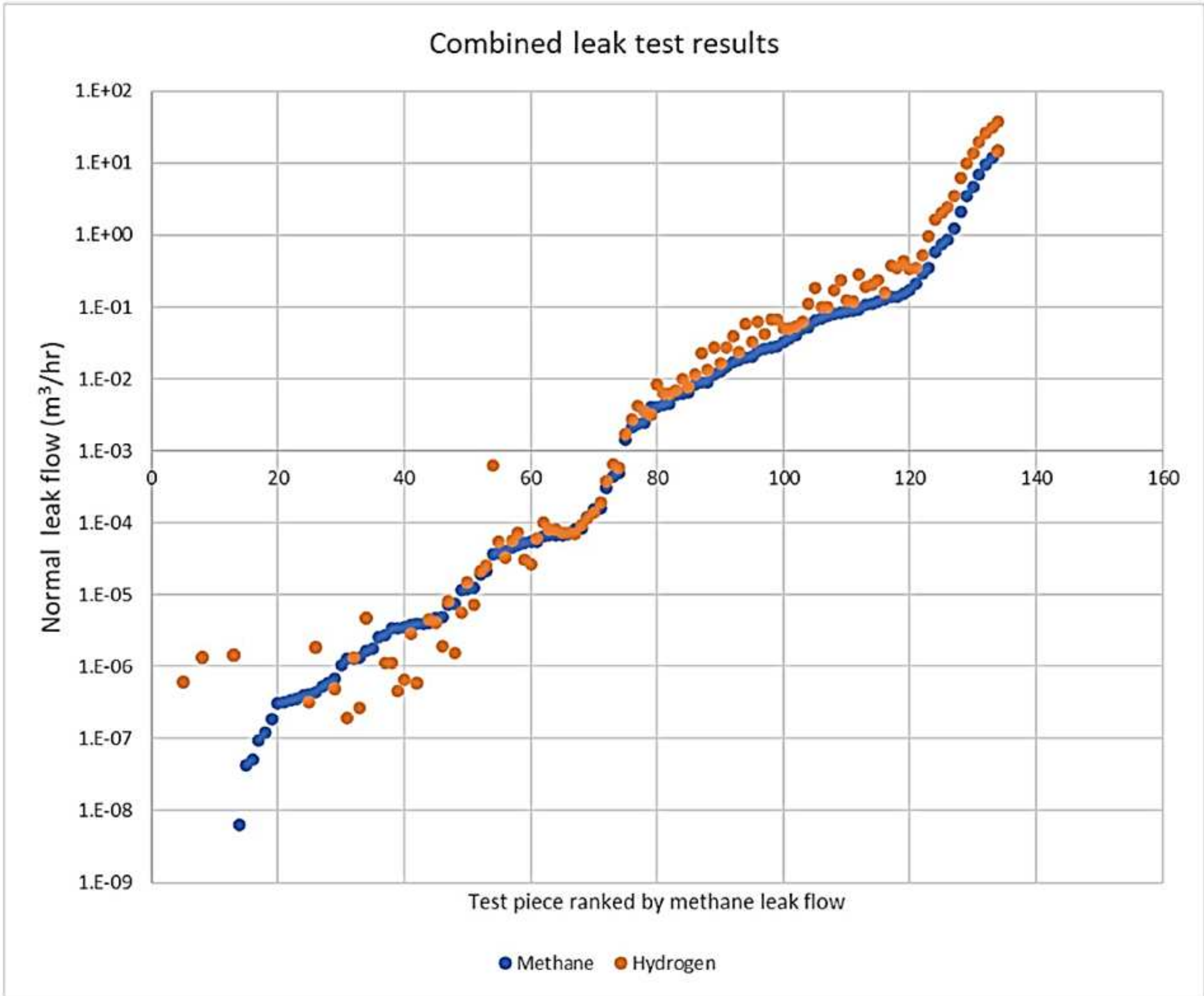
Table 4 lists the leak rates of 40% hydrogen and 60% methane gas blend from the 10 lines, obtained during long-term tests. All leak rates are below the admissible flow rate of 0.1 l/h (3.53 × 10^{-3} cfm) and no increase of leakage rates is observed when compared to short term tests. It is worth noting that one of the test gas lines exhibits negative leak flow rate. The authors point out to the difficulty of obtaining accurate leak flow rates at low pressures, especially with temperature having a significant impact on pressure, and suggest this is in agreement with results obtained from the studies conducted by a Ukrainian consortium and the HyDelta project.

Table 4: Long-term leak rates of 40% H2 and 60% CH_4 gas blend for 10 lines (*89*)

Line num-ber	Volume	P1	P2	T1	T2	ΔP corrected with the temperature	Duration of the test	Leakage rate
	liter	*bar*	*bar*	*°C*	*°C*	*bar*	*hours*	*$l \times h^{-1}$*
L1	0.179	1.0260	0.999	21.447	21.702	0.028	30	1.66×10^{-4}
L2	1.15	1.0342	1.00715	21.49	21.795	0.028	80	4.03×10^{-4}
L3	3.324	1.0358	1.0247	22.92	23.22	0.012	284	1.41×10^{-4}
L4	0.461	1.0358	1.0247	22.92	23.22	0.012	69	8.06×10^{-5}
L5	10.576	1.0335	1.03265	23.561	23.774	0.002	70	2.37×10^{-4}
L6	8.237	1.0349	1.02205	21.984	22.816	0.016	251	5.14×10^{-4}
L7	0.221	1.0372	1.03585	22.54	22.231	0.000	200	2.94×10^{-7}
L8	0.744	1.0360	1.00105	22.443	22.108	0.034	80	3.14×10^{-4}
L9	0.355	1.0355	1.0072	22.4	22.324	0.028	70	1.42×10^{-4}
L10	0.422	1.0355	1.0357	22.078	22.058	0.000	71	-1.61×10^{-6}

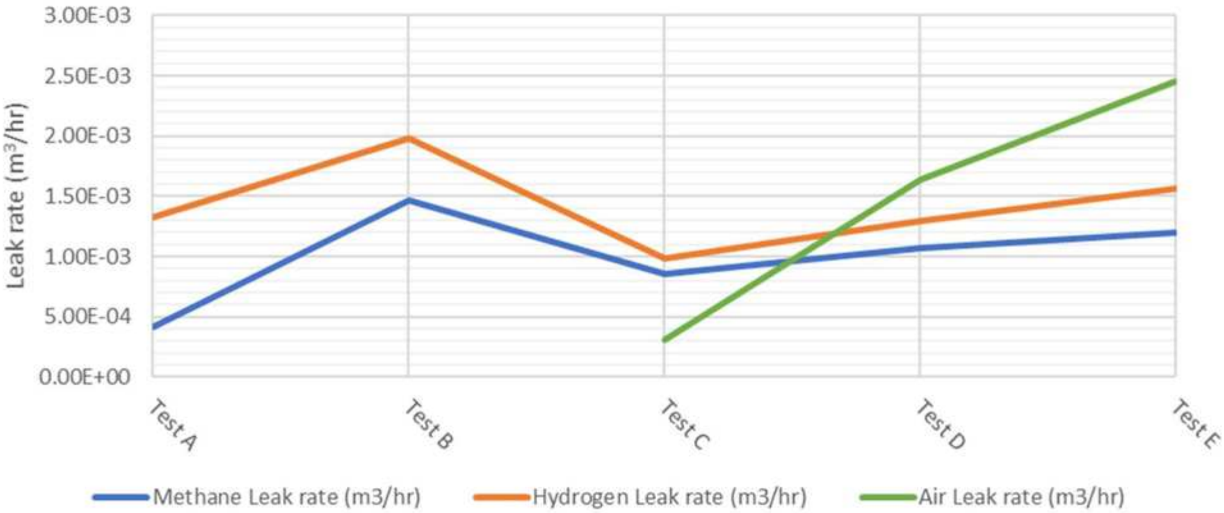
Experimental work conducted as part of the Hy4Heat project, aimed at evaluating the technical feasibility of converting residential and commercial natural gas appliances in Great Britain to use with pure hydrogen gas, included leak testing of various fittings and pipes of domestic natural gas pipeline network (*92*). The components subjected to testing included lead, copper, low carbon malleable iron, stainless steel, and polyethylene pipes, as well as a variety of fittings and valves. The study evaluated the following types of leaks: 1) circular holes in thin and thick wall pipes; 2) thin cracks, circumferentially and longitudinally oriented; 3) thin annular gap such as an unsoldered solder joint; and 4) thread leaks resulting in a helical leak path. Initial testing was conducted under pressures of up to 100 mbar (1.45 psi), with subsequent testing at 20 mbar (0.29 psi), which are common for domestic natural gas systems. The leak flow rates obtained from the tests are presented in Figure 19, with flow rate in m^3/hr (0.589 cfm) presented on a logarithmic scale. The study concludes that for the majority of tests, pure hydrogen leaks at a rate of 1.2 to 2.8 times greater compared to methane. Leaks observed with methane were also observed under tests with hydrogen, and vice-versa, non-leaks with methane translates to no detectable leaks with hydrogen.

Figure 19: Combined leak results for all tests in the Hy4Heat project (*92*)



Subsequent experimental work by the Hy4Heat project evaluated and compared leak rates of hydrogen and methane on commercial natural gas installations including pipes, meters, valves, boilers, and other components (*93*). The results obtained from five tests, each focused on a separate component of the installation, are shown in Figure 20. According to the authors, the data suggest that the system can essentially be considered leak free due to the low leak flow rates, even though the actual leak rates with hydrogen are higher in comparison to those with methane gas.

Figure 20: Measured leak rates for all test in the Hy4Heat project (*93*)



The H21 project investigated whether it is feasible to transport 100% hydrogen via the current natural gas network in Great Britain. During Phase 1 of the project, Health and Safety Executive (HSE) and industry partners leak tested a variety of natural gas piping components representative of the natural gas distribution network in Great Britain with methane and hydrogen (*94*). The study evaluated 210 assets, made of polyethylene, cast iron, spun iron, ductile iron, and steel. Of those, only 41 exhibited leaks and from which only 19 were suitable for leak testing in the measurable leak flow rate range of 100 to 20000 cm^3/min (3.53×10^{-3} to 0.71 cfm). The components tested at the low pressure (LP) range of 20 to 75 mbar (0.29 to 1.1 psi), show ratios of pure hydrogen to methane leak rates between 1.2 and 2.2 (Figure 21), while components tested at medium pressure (MP) of 75 to 2000 mbar (1.1 to 29 psi) and intermediate pressure (IP) of 2000 to 7000 mbar (29 to 101.5 psi) exhibit hydrogen to methane leak rate ratios between 1.8 and 2.6, approximately (Figure 22). The study's findings show that with respect to component material, none of the tested PE assets leaked, a quarter of all iron assets leaked, while only 14% of steel components leaked. Furthermore, four types of joints, including screwed, lead yarn, bolted gland and hook bolts, were primarily responsible for the majority of the leaks. The results showed that for the leaky components, the leaks were present with both pure hydrogen and with pure methane. Likewise, repairs performed on leaking components were equally effective under both hydrogen and methane leak tests.

Figure 21: Ratios of hydrogen to methane leak rates for low pressure assets in the H21 project (*94*)

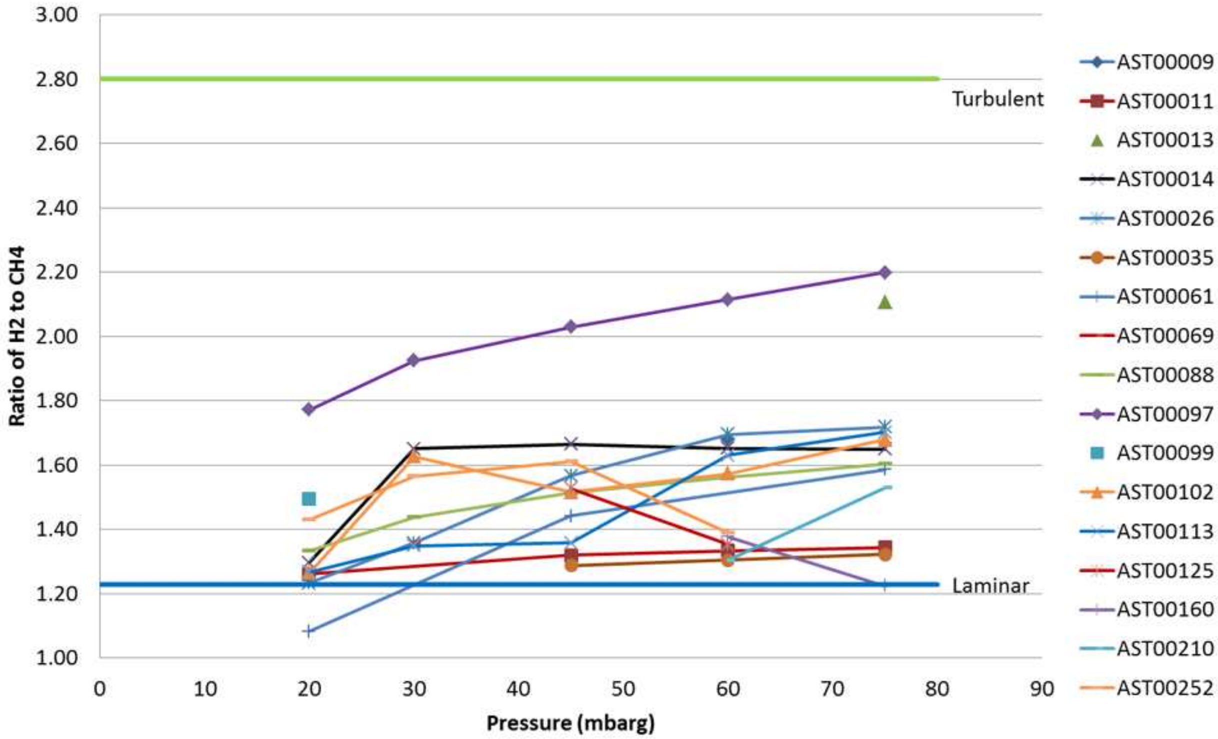
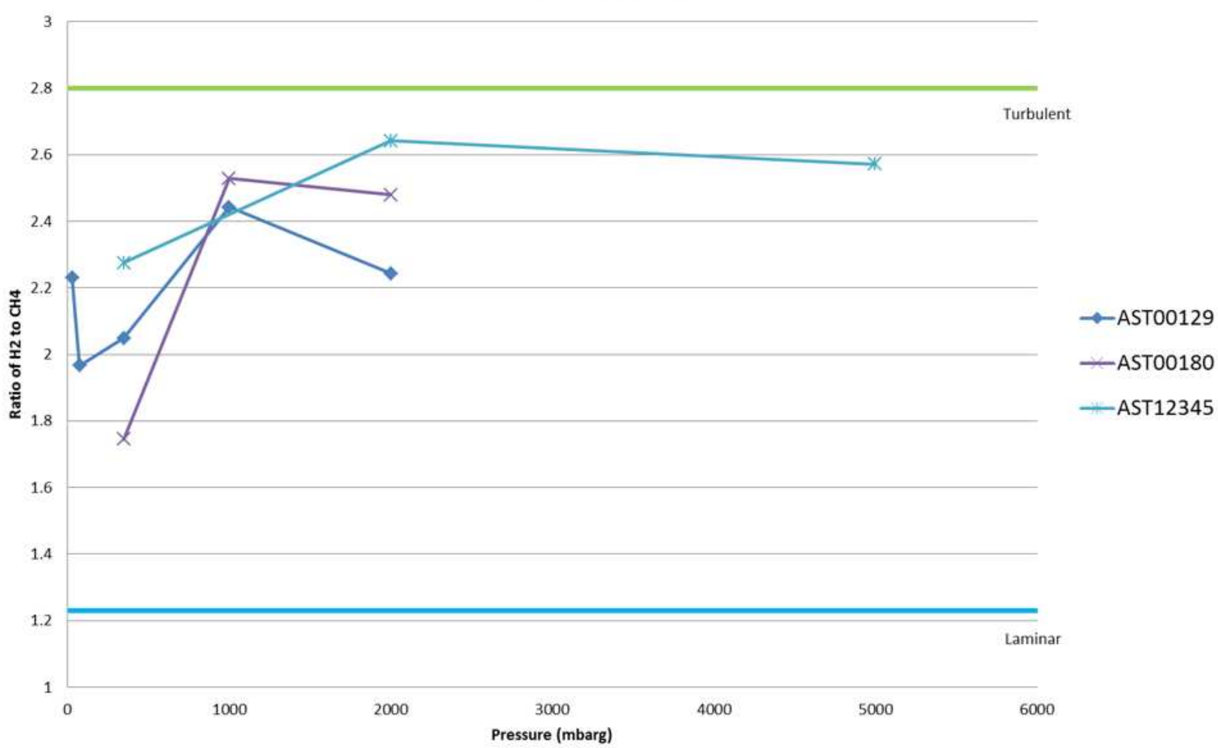


Figure 22: Ratios of hydrogen to methane leak rates for medium and intermediate pressure assets in the H21 project (*94*)



Experimental evaluation of gas leaks from distribution pipes was conducted as part of research efforts undertaken by the HyDelta project in the Netherlands, aimed at identifying and reducing barriers to utilizing existing natural network with pure hydrogen (*95*). Results comparing flow rates of nitrogen, natural gas, and hydrogen from different leaks at pressures from 30 to 300 mbar (0.44 to 4.35 psi), are summarized in Table 5. The ratio of hydrogen leak flow rate to that of natural gas varies from 1 to 3.4, with an average of approximately 1.7.

Table 5: Average leak flow rates of nitrogen, natural gas, and hydrogen, with their respective ratios in the HyDelta project (*95*)

leak no.	pressure [mbar]	avg. φ N_2 [l/h]	avg. φ natural gas [l/h]	avg. φ H_2 [l/h]	φ natural gas / φ N_2	φ H_2 / φ natural gas	φ H_2 / φ N_2
1A	30	0.29	0.44	0.46	1.51	1.05	1.59
	100	0.92	1.00	1.56	1.09	1.56	1.70
	200	1.39	1.59	2.78	1.14	1.75	2.00
1B	30	0.95	1.23	1.70	1.29	1.38	1.79
2A	30	0.25	0.53	0.53	2.12	1.00	2.12
	100	0.52	0.56	1.37	1.07	2.45	2.63
	200	0.92	1.26	2.36	1.37	1.87	2.56
2B	30	1.52	2.61	3.38	1.71	1.30	2.22
	100	3.93	5.89	10.01	1.50	1.70	2.55
3A	30	0.27	0.12	0.41	0.44	3.42	1.52
	100	0.54	0.70	1.43	1.30	2.04	2.65
	200	1.10	1.21	2.35	1.10	1.94	2.14
3B	30	1.04	1.61	2.40	1.55	1.49	2.31
	100	3.05	4.31	7.08	1.41	1.64	2.32
4A	30	0.37	0.37	0.52	1.00	1.41	1.41
	100	1.07	1.38	2.30	1.29	1.67	2.15
	200	1.81	2.28	3.92	1.26	1.72	2.17
4B	30	0.88	1.26	2.01	1.43	1.60	2.28
	100	2.12	3.03	5.52	1.43	1.82	2.60

Enertek conducted an independent study, commissioned by The Environmental Coalition on Standards (ECOS), comparing the leakage rates of natural gas, pure methane, pure hydrogen, and a gas blend 20% hydrogen and 80% methane, in household natural gas appliances and pipework (*96*). Leakage rate was quantified by pressure drop in the system over time while appliances were in a stand-by mode. Leakage rates through threaded fittings, gas cooktop control valves, and boiler control valves were assessed at a maximum pressure of 25 mbar (0.36 psi) by recording the pressure drop in each test gas line over the period of 20 min. Figure 23 shows the pressure drops in three gas cooktops tested with pure methane gas (G20) and 20% hydrogen methane blend (referred to as G20.2) pressurized at 21 mbar (0.31 psi). In the *cold* condition tests were conducted with appliances at room temperature, while for the *hot* test condition, the appliances were turned on for 10 min and then turned off prior to the test. Tests on all three appliances, in both cold and hot conditions, indicate that the hydrogen and methane gas blend leaks at higher rate than pure methane. Figure 24 shows the pressure drop measurements obtained from three household boilers tested with pure methane gas (referred to as G20) and 20% hydrogen methane blend (referred to as G20.2) at an internal pressure of 21 mbar (0.305 psi) under the cold and hot test conditions. These data indicate that the gas blend containing 20% hydrogen and 80% methane leaks at a higher rate than pure methane for all three boilers tested under both *cold* and *hot* conditions.

Figure 23: Pressure drop in cooktops with CH_4 and blend of 20% H_2 in CH_4 (*96*)

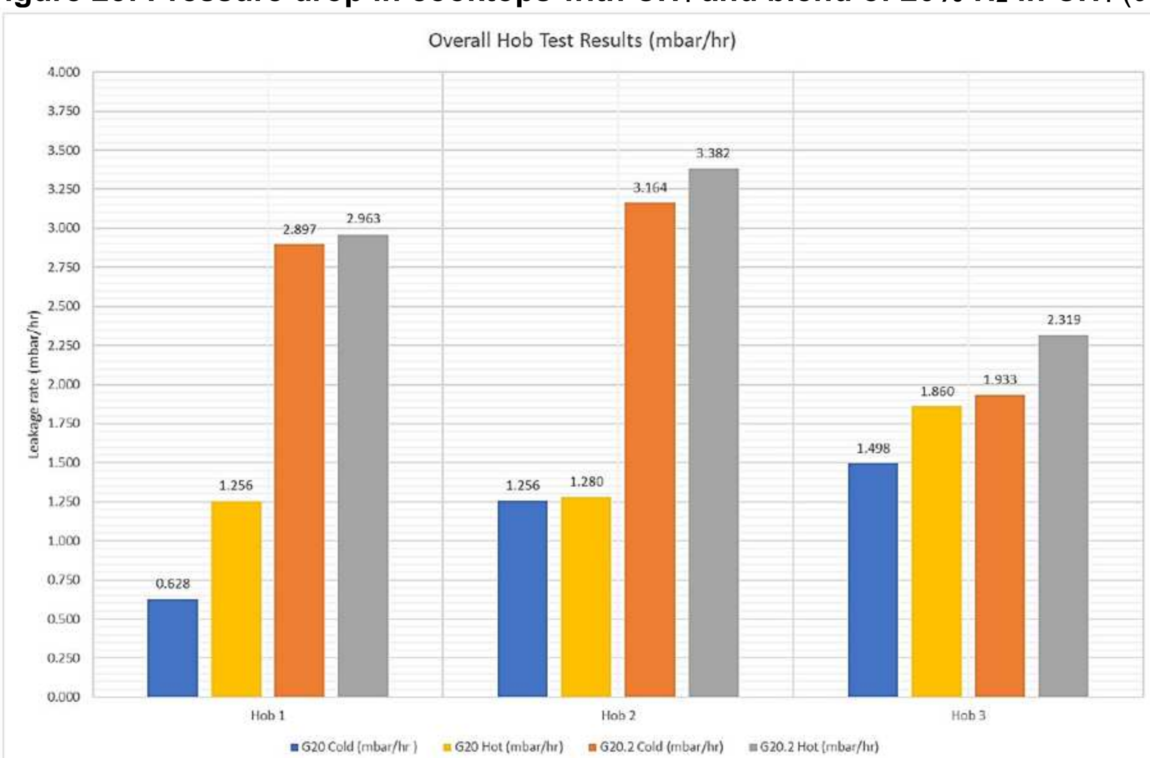
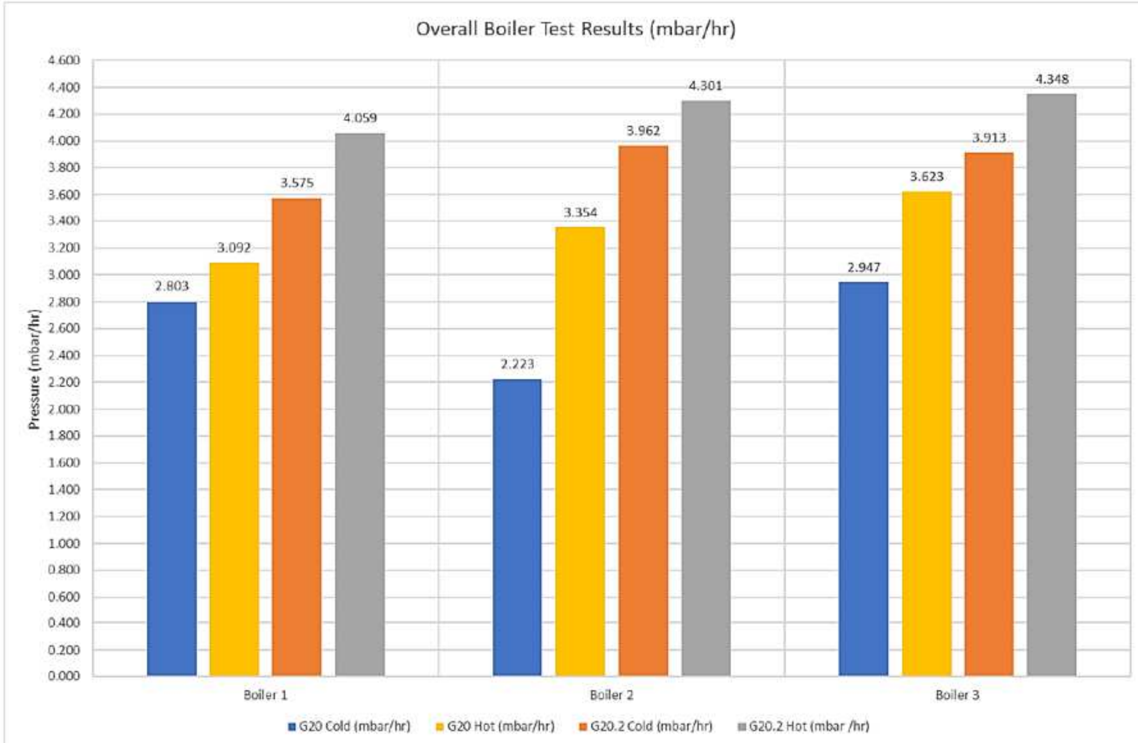


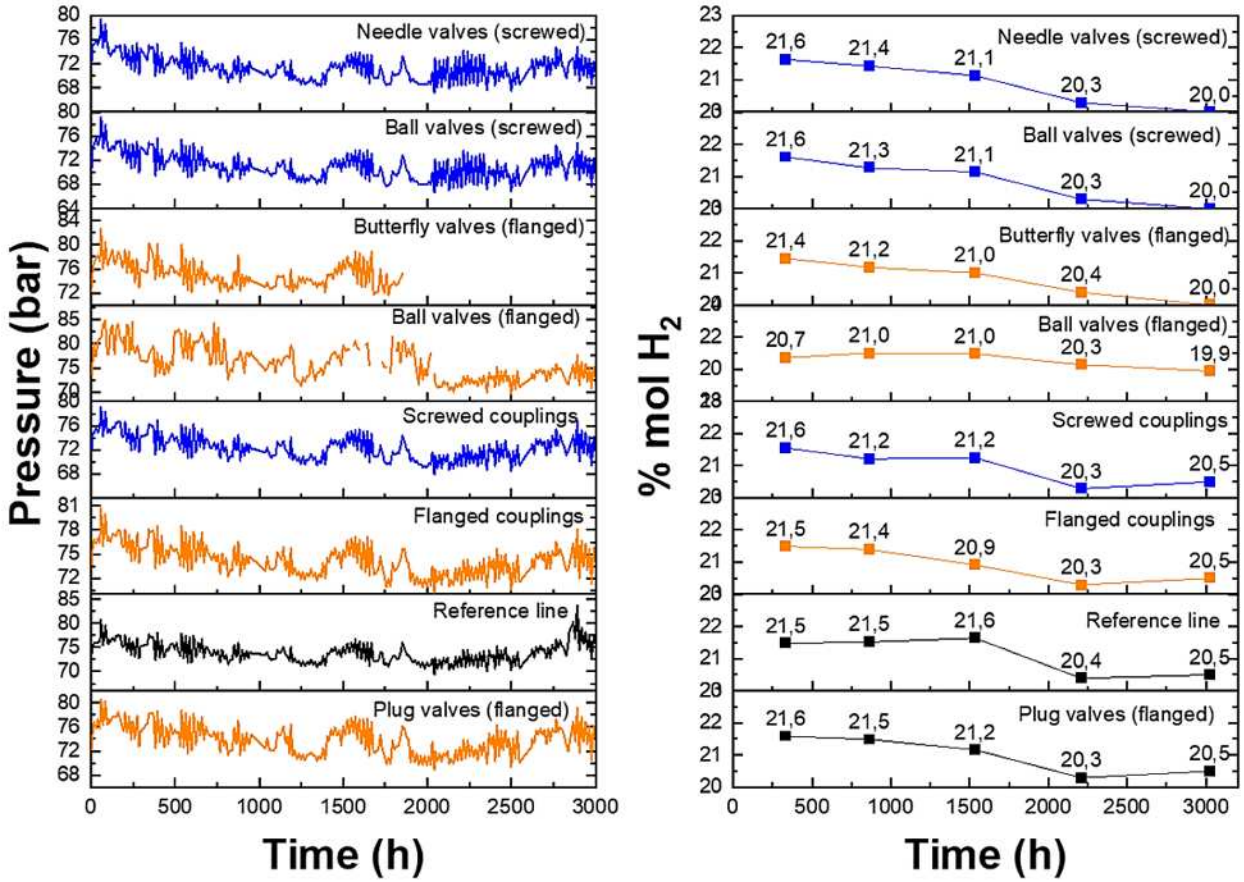
Figure 24: Pressure drop in boilers with CH_4 and blend of 20% H_2 in CH_4 (*96*)



Research work conducted under the European project Hydrogen in Gas Grids (HIGGS) included leak testing of various valves commonly employed in the natural gas systems, with a gas blend of 20% hydrogen and 80% methane (*97*). The tests were conducted at a pressure of 80 bar for 3000 hours. Figure 25 (left) shows the pressure change over time in the different test lines containing various types of valves or fittings, and a reference line which does not contain any component. Figure 25 (right) shows the molar concentration of hydrogen in methane inside the test gas lines, measured periodically by gas analyzer. The pressure measurements for all test gas lines indicate no significant change in pressure over time, suggesting no leaks exist. The oscillations of measured pressures are attributed to temperature variability. The hydrogen concentration in all gas lines decreases roughly by 1%, however the authors point out that measurement error of the gas analyzer used is 1%.

The HIGGS project conducted additional gas leak studies in on gas couplings and valve components with a gas blend of 30% hydrogen and 70% methane at a static pressure of 80 bar (*98*). The results after 1400 hours of testing revealed a gas leak in only one test line containing screwed ball valves. The leak was attributed to the absence of internal sealing capacity, and all three valves of that type that were tested exhibited leaks. With regards to the hydrogen concentration measured in all test gas lines, less than 1% change was observed, including the one gas line which was leaking through the screened ball valves.

Figure 25: Pressure (left) and gas concentration in % mol H_2 (right) over time (*97*)



Experimental investigations into the gas tightness of common domestic meters when used with pure hydrogen gas were conducted by the NewGasMet project (*99*). A diaphragm gas meter was tested at a pressure of 1100 mbar (15.95 psi), after 8 days of static pressure testing a total pressure drop of 6 mbar (0.087 psi) was observed, equivalent to an average of 0.75 mbar (0.011 psi) per day. Thus, the observed leak rate was lower than the critical pressure drop of 1.8 mbar (0.026 psi) per day.

The HyDeploy 2 project conducted frequent gas leak checks throughout the demonstration period (*83*). Analysis of collected data suggested that blending of 20% hydrogen in the natural gas distribution network did not lead to an increase of leaks identified during the project.

The Testing of Blends of Hydrogen and Natural Gas (HyTest) project evaluated feasibility of safely operating residential natural gas end-use equipment in Ireland with blends of natural gas containing from 2% to 20% hydrogen (*100*). Leak and safety testing appliances, with gas blends containing 2%, 5%, 10%, 15% and 20% hydrogen in natural gas. Testing consisted of measuring the pressure drop over 4 min in test lines with an initial pressure of 20 mbar (0.29 psi). The findings of these tests revealed no change in pressure in the tested gas lines, signifying no leaks.

The H2SAREA project conducted an assessment of operation of a test gas line loop representative of the natural gas distribution system in Spain, using a natural gas blend containing 20% hydrogen for 3000 hours (*60*). Gas leak detection checks were performed throughout the project on 552 critical points of the test loop, including flanged joints, welding, taps, valves, steel pipes, polyethylene pipes, steel-polyethylene and polyethylene-copper transitions, domestic receivers, meters, internal copper connections, appliance regulators, appliance taps and others. Gas leak tests were performed on two lines at pressures of 4 bar (58 psi) and 16 bar (232 psi), respectively. The study concluded that no leaks were identified in the system.

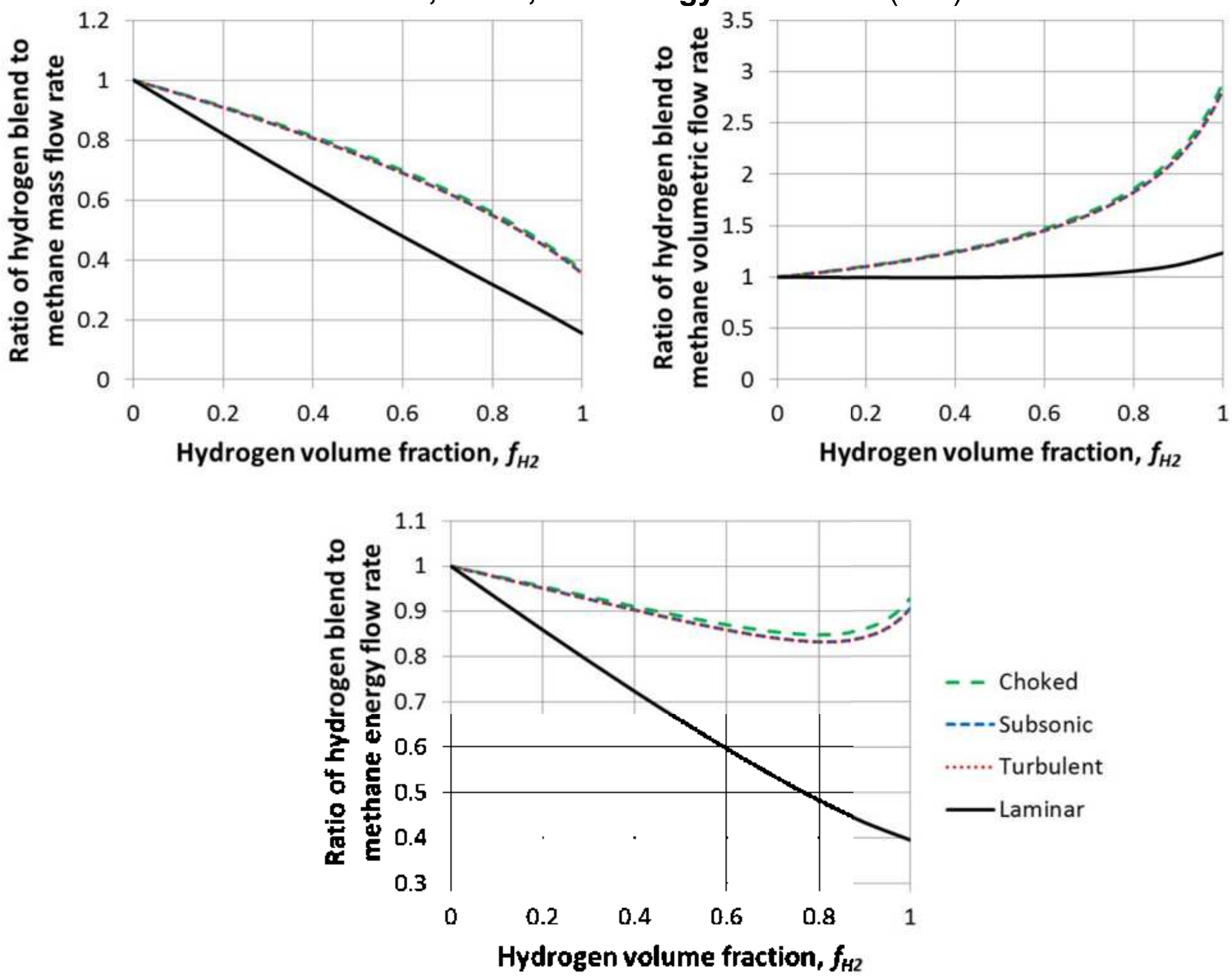
Another demonstration project, Hydrogen Park South Australia, evaluated gas leaks from the natural gas system after blending 5% renewable hydrogen in the natural gas network in Adelaide, Australia (*84*). Leak tests prior to hydrogen blending and after 12 months of operation on gas blend of 5% hydrogen did not identify any leaks.

Quantifying hydrogen loss due to leakage in natural gas systems

A review of recent literature did not identify any reports that directly estimate the amount of hydrogen lost to the environment from a specific natural gas network due to blending hydrogen in natural gas at specific concentrations. However, studies have presented comparisons of existing gas leaks in the natural gas infrastructure and anticipated changes due to hydrogen blending at different concentrations. A number of experimental and numerical studies have shown that an increase in hydrogen blending concentrations in natural gas or methane leads to increased volumetric leak flow rates, when all other test conditions such pressure, temperature, and leak size, remain constant (*101–103*). This effect is attributed to different thermophysical properties of hydrogen and hydrogen blends, such as lower density and viscosity of hydrogen in comparison to methane. Using these differences of physical properties, gas leaks rates for different gas blends could be estimated numerically for simple leak geometries and common gas leak mechanisms.

Grant *et al.* numerically evaluated the leak flow rate ratio of gas blends of hydrogen and methane to pure methane (*101*). Figure 26 shows the results for blends containing 0% to 100% hydrogen in methane, plotted on volumetric, mass, and energy flow basis. Four different flow mechanisms, consisting of laminar, turbulent, choked, and subsonic flows are compared. Turbulent, choked, and subsonic flow regimes result in flow rates significantly greater than laminar flow but these three regimes produce very similar flow rates. Leak rate ratio of hydrogen gas blend to pure methane on energy and mass flow rate basis should also be considered in addition for volumetric flow rate basis, which is typically used to report flow rates by most studies. Based on volumetric flow rate basis, blends containing hydrogen have larger flow rates, although under laminar flow, blends containing less than 60% hydrogen show similar flow rate to pure methane. If mass flow rates or energy flow rates are considered, gas blend containing any concentration of hydrogen in methane would leak at lower flow rates than methane.

Figure 26: Leak flow rate ratio of hydrogen-methane blend to methane, shown on volumetric, mass, and energy flow basis (*101*)



Hydrogen permeation is another potential pathway for hydrogen loss. However, leakage mechanisms have significantly higher potential for hydrogen loss than permeation. The permeation of hydrogen gas through the materials used in natural gas networks is more significant in polymers such as polyethylene, commonly used in distribution pipelines, than it is in steels used in both transmission and distribution pipelines. Nevertheless, estimates of hydrogen loss due to permeation through in MDPE, HDPE, and PA11 pipes, discussed in Chapter 3, suggest relatively low loss rates (0.066%, 0.019%, and 0.011% per year, respectively) (*54*).

Dispersion characteristics of hydrogen blend leaks and risk assessment

One of the primary concerns associated with gas leaks or releases of hydrogen blended with natural gas is the elevated fire hazard of hydrogen compared to natural gas or pure methane. Hydrogen has a broader range of flammability when mixed with oxygen compared to methane, lower ignition energy, and higher flame propagation velocity (*104*, *105*). However, hydrogen's stoichiometric concentration[10] in air is 29.5%, while that of methane is only 9.5%. When released in air hydrogen disperses differently than methane, since hydrogen is more buoyant and diffusive (*106*). To accurately assess and quantify fire hazard risks associated with gas leaks of hydrogen blended with natural gas it is necessary to evaluate the dispersion behavior of these gases upon release in different environments, as well as ignition and flame properties. It should be noted that the flammability and other relevant properties of hydrogen-natural gas blends will depend on the percentage of hydrogen in the blend and the associated bulk properties of the gas mixture.

The Hy4Heat project conducted extensive experimental work and modeling of dispersion of hydrogen gas in air in comparison to methane in air, in a residential home and enclosed spaces such as cupboards (*91*). The gas dispersion assessment and report from Hy4Heat project also includes experimental test findings from projects HyHouse and H100, which consist of dispersion tests in an old cottage and simulated kitchen environment, respectively (*107*). Figure 27 summarizes all test results in terms of measured concentration of released gas in air (GIA) in a room or confined space for hydrogen and methane gases at different leak rates shown on an energy basis instead of volumetric flow rate. These test results were obtained through continuous gas sampling with sensors positioned at different locations in house rooms, cupboards, and basements. As shown in Figure 27, the leaks of hydrogen and methane under different scenarios exhibit two distinct patterns, however under both trends the concentration of hydrogen in air is similar to that of methane, with hydrogen concentration being slightly greater in some cases. Furthermore, the findings of these tests suggest that hydrogen

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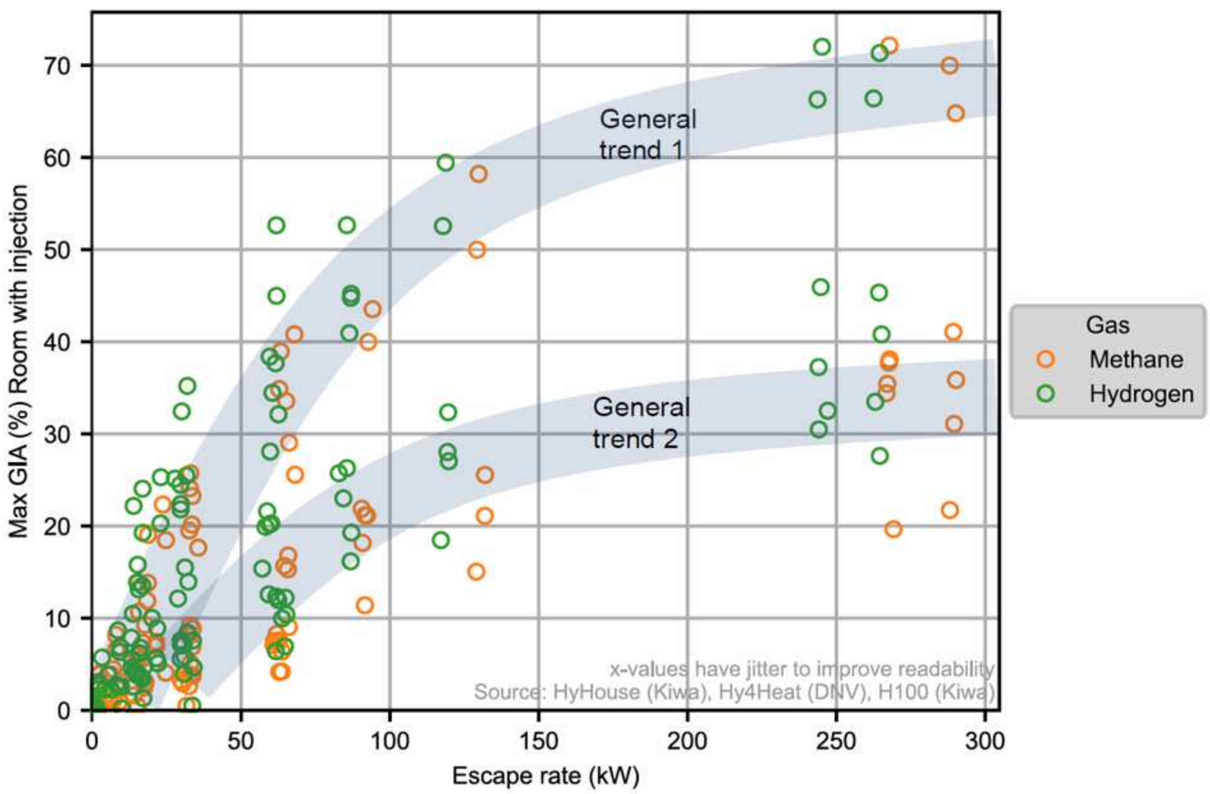
[10] The specific proportion of fuel to air under which complete combustion occurs with no excess fuel or oxygen remaining.

tends to accumulate slightly quicker than methane at the top or middle of a room upon release.

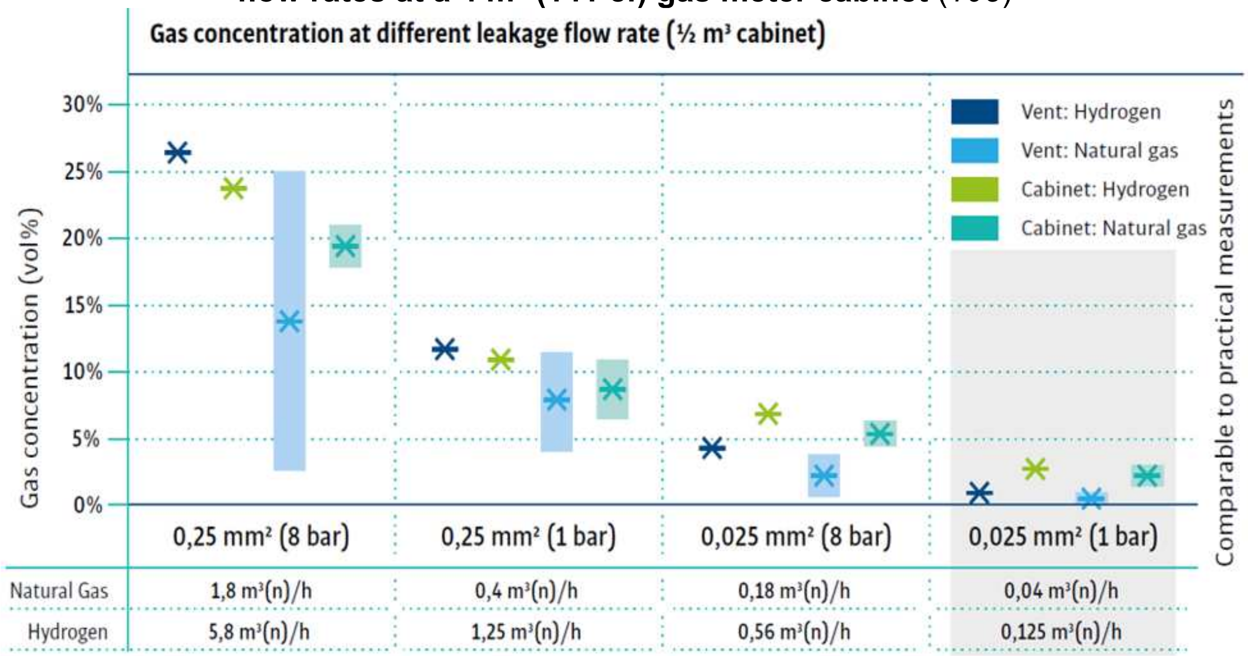
Figure 27: Maximum concentration of released gas in air (GIA) for methane and hydrogen (*107*)



The H21 project investigated the release and dispersion behavior of hydrogen and methane gases in three residential houses and gardens (*90*). Simulated leaks with diameters of 5.1 and 20 mm (0.2 and 0.79 in) from distribution service lines located in basement, kitchen, and cupboard were evaluated for gas release and accumulation. Tests were conducted at line pressures of 5, 20, 30, and 75 mbar (0.073, 0.29, 0.44, and 1.09 psi). The results of the tests revealed that higher volumetric flow rate leaks resulted in higher concentrations of hydrogen and methane in air. However, for the same volumetric flow rate for methane and hydrogen at a given leak location, hydrogen concentrations in air were lower than methane. On the other hand, at a given fixed pressure and leak diameter, the released hydrogen stratification was greater than methane for high flow rate leaks, while for low flow rate leaks stratification of the two gases was comparable.

The HyDelta 2 project conducted comparative assessment of release and dispersion of hydrogen and natural gas in a room with volume of 26 m³ (918 cf) and a hall with volume of 10 m³ (353 cf) with a gas meter cabinet (*108*). The results of the study suggest that at leak flow rates of 50 l/h (0.029 cfm) both hydrogen and natural gas concentrations in the gas cabinet and room remain below 100% of lower flammability limit (LFL) if the gas meter cabinet is fitted with the vents prescribed for natural gas. Figure 28 shows concentrations of hydrogen and natural gas in air for different leak flow rates in 4 m^3 (141 cf) gas meter cabinet.

Figure 28: Gas concentrations in air of hydrogen and natural gas at different leak flow rates at a 4 m³ (141 cf) gas meter cabinet (*108*)



With respect to a gas blend of 20% hydrogen in natural gas, work conducted by project HyDeploy suggests that the dispersion characteristics of the gas mixture are comparable to that of natural gas (*109*). Additionally, the leak flow rate of a gas blend containing 20% hydrogen in natural gas could result in 10% higher volumetric leak flow rate under turbulent flow rate conditions. However, in terms of energy flow rate, the gas blend flow rate would be lower compared to natural gas for an identical leak geometry and pressure conditions. With respect to flammability limits, the LFL of the gas blend (20% hydrogen) is 4.75%, compared to 5% for natural gas (*109*).

Grant *et al.* calculated concentrations of methane, hydrogen, and 20% and 50% hydrogen blends as percentage of their respective LFL (*101*). Figure 29 and Figure 30 demonstrate the results for an enclosed space with dimensions of 1 by 1 by 0.5 m (3.28 by 3.28 by 1.64 ft), with ventilation openings on top and bottom which are 1 m (3.28 ft) across and have a width of 0.05 mm (0.002 in). With equivalent volumetric leak flow rate of the four gases (Figure 29), concentrations of the four gases as percentage of LFL are very similar after 25 hours. On the other hand, when equivalent energy flow rates are considered (Figure 30), the gases containing hydrogen exhibit an increased concentration with the increasing content of hydrogen in the gas mixture.

Figure 29: Predicted concentration of leaked gas in a 1 × 1 × 0.5 m (3.28 × 3.28 × 1.64 ft) enclosure based on equivalent volumetric flow rate (*101*)

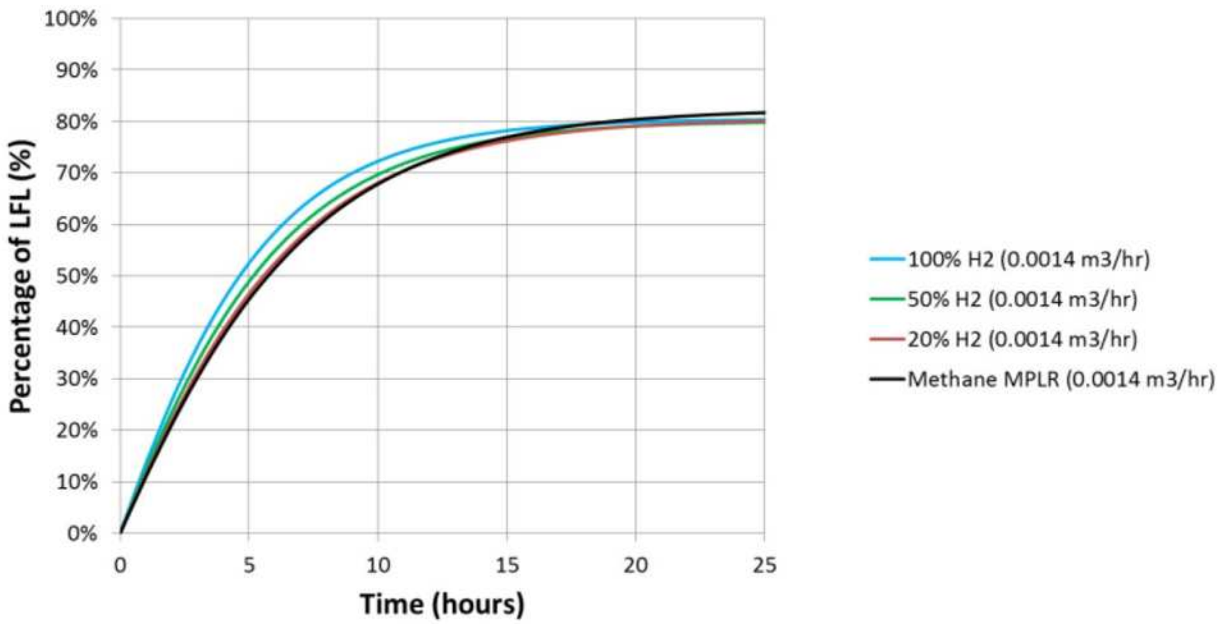
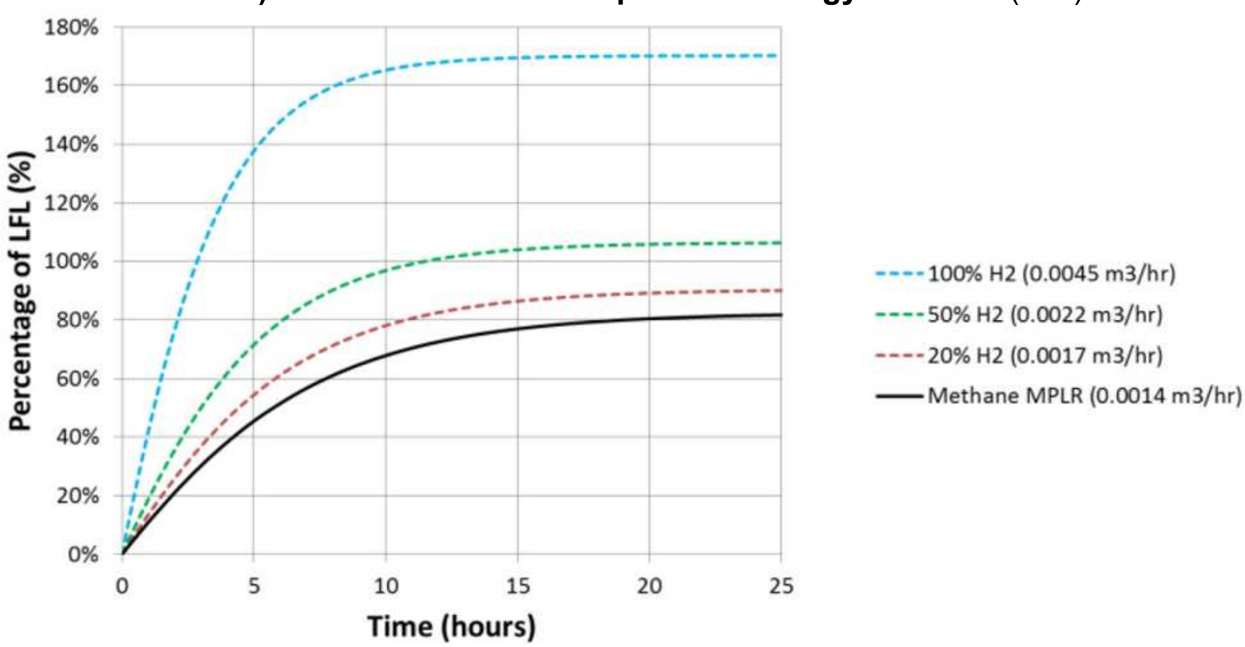


Figure 30: Predicted concentration of leaked gas in a 1 × 1 × 0.5 m (3.28 × 3.28 × 1.64 ft) enclosure based on equivalent energy flow rate (*101*)



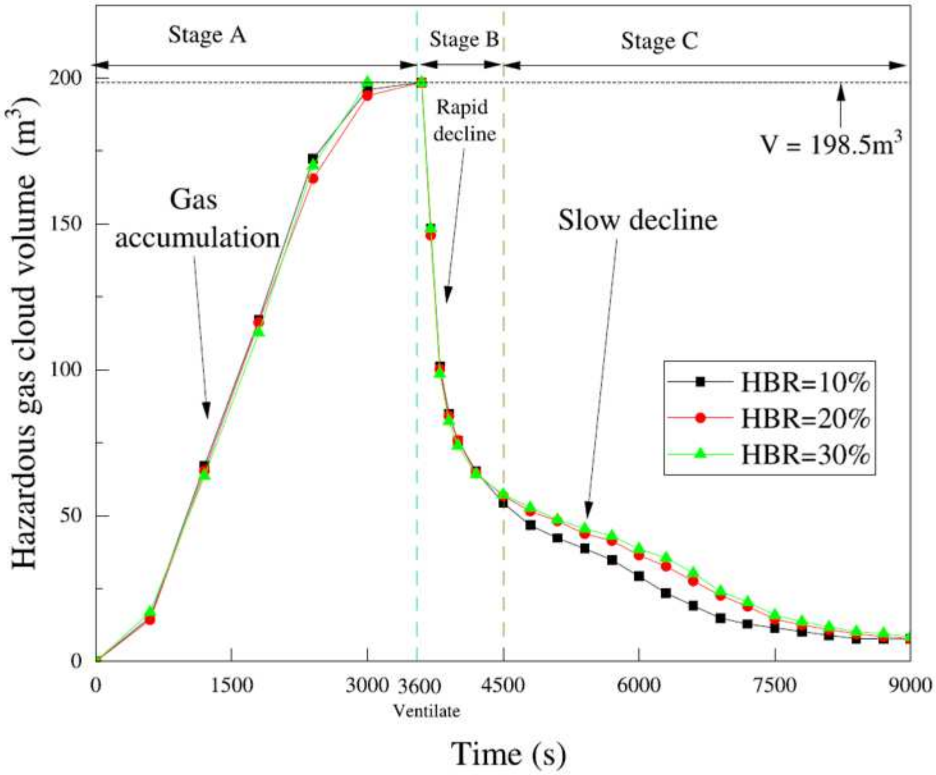
Modeling of release and dispersion of hydrogen and hydrogen-methane gas blends is often accomplished using computational fluid dynamics (CFD) and Large Eddy

Simulation (LES), with ANSYS Fluent and GASFLOW-MPI being some of commonly used software packages (*110*). Su *et al.* investigated release and dispersion characteristics of blends of hydrogen and natural gas in a domestic kitchen using ANSYS Fluent (*111*). The results of the study demonstrated that at a constant leak rate, an increase of hydrogen concentration in the blend results in decreased alarm time and the time to reach lower explosion limit. Xu *et al.* also employed ANSYS Fluent software to investigate the leakage distribution and concentration of hydrogen blended natural gas in a domestic kitchen (*112*). The numerical investigation revealed that leaked gas tends to accumulate at top of the simulated space, and an increase in the concentration of hydrogen in the blend leads to increase in dispersion capacity of leaked gas. Thawani *et al.* employed K-epsilon turbulence model to investigate leakage characteristics of pure hydrogen and methane in confined spaces in a kitchen, with leak diameters from 1.8 to 7.2 mm (0.071 to 0.284 in) (*113*). The results of the study revealed that at greater volumetric flow rates, achieved with the 7.2 mm (0.284 in) diameter aperture, hydrogen gas reaches equilibrium 45 sec faster than methane.

Li *et al.* investigated concentration, accumulation, and ventilation of gas leaks of hydrogen at concentrations of 10%, 20% and 30% blended with natural gas in a domestic house through CFD modeling (*114*). The volume of accumulated leaked gas in the house is almost identical for all three gas blends, shown as Stage A in Figure 31. During the ventilation process, when all windows and doors are opened, the volumes of all three gas mixtures decrease at the same rate in Stage B, while volume of the 10% hydrogen blended natura gas decreases quicker in Stage C, as evident from Figure 31.

Several studies have specifically investigated the dispersion behavior of hydrogen and methane in utility tunnels, primarily through modeling work. Shao *et al.* developed a 3D CFD model of a utility tunnel in China, to compare the dispersion of hydrogen and methane from a pipe through a 20 mm (0.79 in) diameter hole, at pressure of 10 bar (145 psi) (*115*). The numerical results suggest hydrogen has greater dispersion velocity and results in a higher concentration compared to a methane leak. Yang *et al.* demonstrated through CFD simulation that peak concentration from a gas leak of hydrogen blended with methane in a utility tunnel increases with increase in concentration of hydrogen in the blend (*116*). These findings have been confirmed by Wang *et al.*, who showed that methane blends with 5%, 10%, 15% and 20% hydrogen, result in higher release concentrations by 2.15%, 4.14%, 7.76%, and 10.97%, respectively (*117*). Han *et al.* demonstrated through a CFD study that when the blended concentration of hydrogen exceeds 20%, safety risks associated with a gas leak in a tunnel are greater compared to natural gas. However, the pressure in gas line, the size of the leak, and the ventilation of the tunnel also play a significant role in safety risks (*118*).

Figure 31: Volume of released gas during accumulation and ventilation (*114*)



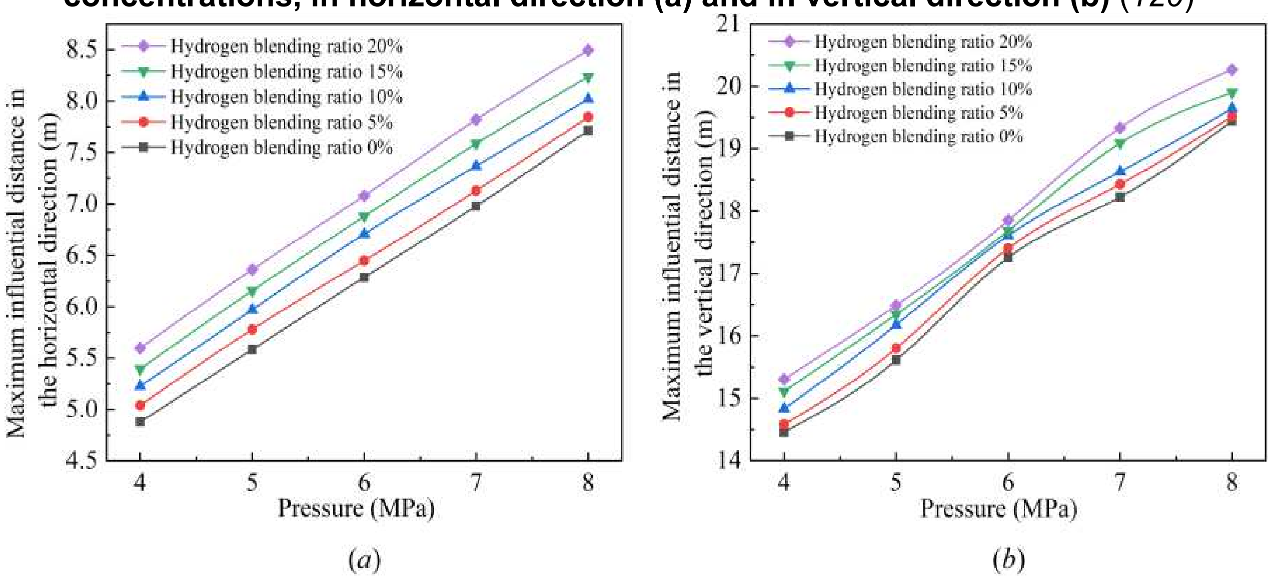
Numerous studies have investigated the release and diffusion of hydrogen blended with natural gas or methane from pipelines buried in the ground. Liu *et al.* demonstrated through a CFD numerical study that subterranean pressures influence underground hazard radius[11] of a pipeline carrying 20% hydrogen blended in natural gas are larger than those of the natural gas pipeline by 15.4% and 11.9%, respectively, while the above-ground danger height is 34.0% higher (*102*). Lu *et al.* conducted a CFD numerical study which revealed that as the hydrogen blending concentration in natural gas increases, the diffusion rate in soil and LFL increase, while an increase in soil porosity also raises diffusion rates (*119*). Liu *et al.* examined numerically the effects of pressure, wind speed, the size of the leak orifice, as well as the hydrogen blending concentration in methane on the diffusion range of a leak from a buried pipeline (*120*). The findings show that near the leakage point, methane concentrations are well above the upper explosive limit, while hydrogen concentrations remain within the explosive

[11] The distance from the gas leak source, where the concentration of flammable gas in the air is within the lower and upper flammability limits.

limit range, but hazardous range for leakage and diffusion of hydrogen-blended natural gas is greater compared to natural gas alone. Horizontal and vertical ranges of the leak increase with increase of hydrogen concentration in the blend, as shown in Figure 32. Li *et al.* developed a 3D CFD model to evaluate the leakage characteristics of hydrogen and hydrogen-methane gas blends from low and medium pressure buried pipelines (*121*). The study reveals that when the hydrogen blending ratio is increased, it speeds up the diffusion process and reduces the first dangerous time[12] (FDT), thus posing greater risk on pipeline safety. Furthermore, the study discovered that harder soils have the ability to limit gas dispersion, leading to an increase in localized concentrations. Bu *et al.* conducted numerical analysis of leakage and diffusion characteristics of underground gas leaks from a buried pipeline with hydrogen blended natural gas (*122*). The study demonstrated that the diffusion range of leaked gas in soil is broader for hydrogen blend compared to methane, with higher pressure and velocity values. Additionally, the results revealed that as the hydrogen blending ratio increases, the hazard radius for a hydrogen gas blend leak also expands.

Another numerical study conducted by Su *et al.* investigated leakage and diffusion from buried pipeline carrying hydrogen blended natural gas (*123*). It also established that increase in hydrogen concentration in gas blend reduces FDT, specifically for hydrogen concentration in methane of 5%, 10%, 15% and 20%, the corresponding FDT is 1053 sec, 1041 sec, 1019 sec and 998 sec, respectively.

Figure 32: Maximum diffusion distance of various hydrogen blend concentrations, in horizontal direction (a) and in vertical direction (b) (*120*)



12 The instance after the onset of fire, when conditions become life-threatening.

Zhu *et al.* developed a large-scale experimental system to simulate high-pressure hydrogen blended natural gas leaks from pipelines buried in the ground in three distinct directions through small holes (*124*). Utilizing experimental data, the authors developed a quantitative model for the relationship between the concentration of hydrogen in natural gas and the diffusion distance over which the released gas reached the lower limit of the explosion. Zhu *et al.* established and validated by experimental work a model for leak flow rate from buried pipelines carrying different blending concentrations of hydrogen (*125*). The model shows that as blended hydrogen concentration increases by 10%, 20%, and 30%, the mass flow rate decreases by 6.59%, 13.77%, and 19.96%, respectively. Wu *et al.* employed ANSYS Fluent to study the diffusion behavior of hydrogen blended natural gas released from small leaks in underground pipelines (*126*). Findings from the study suggest that an increase in hydrogen blending concentration results in higher overall danger by reaching lower explosive limits faster, wider hazardous regions, lower explosive limits for the combined gas, and a faster rate of hydrogen concentration.

Li *et al.* investigated the characteristics of a large scale fire from hydrogen and hydrogen blended with natural gas, based on an ANSYS Fluent 3D CFD model (*127*). It was revealed that at an equal pressure leak, the thermal radiation hazard distance[13] decreases as the hydrogen concentration in the gas blend rises from 0% to 100%. However, when the hydrogen blending ratio is below 22%, the reduction in the thermal radiation hazard distance is less pronounced. Wang *et al.* developed a numerical two-stage model to investigate the jet characteristics and subsequent diffusion mechanism from hydrogen blended natural gas leaks, at hydrogen concentrations from 0% to 20% (*128*). The study discovered, that increase in hydrogen concentration leads to increase in explosion hazardous distance[14] (Figure 33).

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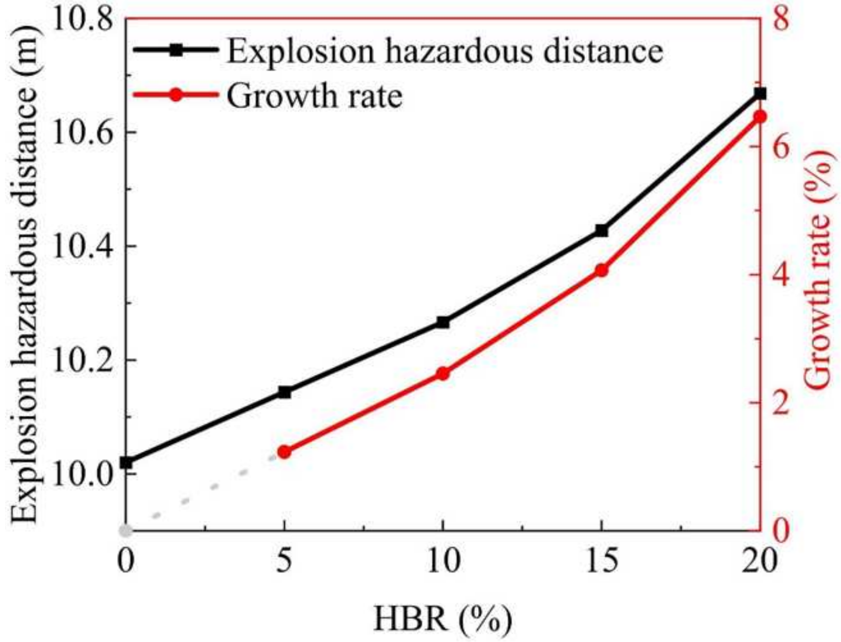
[13] The maximum distance from fire or heat source at which the intensity of thermal radiation is sufficient to cause damage.

[14] The maximum distance from the gas leak source at which the flammable gas concentration in the air is within the lower and upper flammable (explosive) limits.

Figure 33: Explosion hazardous distance of hydrogen blended natural gas leak at different hydrogen concentrations (*128*)



Multiple studies have used numerical models to investigate the effect of hydrogen blending in natural gas on the release and dispersion behavior from leaks in pipes in different environments. Mei *et al.,* based on a CFD model, demonstrated that in a leak in open space, increase in hydrogen blending concentration in natural gas leads to faster dissipation of the combustible gas cloud and reduced influence range[15] (*129*). Cerbarano *et al.* investigated hydrogen blended natural gas leaks from pipelines at pressure of 1.5 to 4.5 MPa (218 to 653 psi) and discovered that an increase in hydrogen concentration increases the diffusivity of the resulting flammable cloud (*130*).

Li *at al.* used a 3D CFD model to evaluate the effect hydrogen blending concentration in natural gas on leak from transmission line in a mixing station and demonstrated that the range of hydrogen gas cloud increases with an increase of hydrogen concentration in the gas blend (*131*). Wang *et al.* developed a mathematical model for non-adiabatic leak of hydrogen blended natural gas from a transmission pipeline 10 km (6.21 mi) long with a diameter of 1016 mm (40 in) (*132*). The model revealed lower mass leakage velocity and a shorter leakage period with increased hydrogen concentration in the gas blend. Jia *et al.* used a 3D CFD model to evaluate the dispersion behavior of hydrogen-methane mixture leak in a compressor plant and demonstrated that increase in hydrogen concentration can increase explosion risk in the vicinity of the leak source (*133*). Li *et al.* used a numerical method to simulate the diffusion behavior of hydrogen

[15] The maximum distance at which the released flammable gas in the air presents a fire hazard.

blended natural gas leak in a close container (*103*). They discovered that gas blends containing up to 20% hydrogen in methane have similar diffusion characteristics to pure methane, while higher hydrogen concentrations result in increased flammable area[16].

Fetisov *et al.* numerically evaluated fire hazard risks from gas pipeline rupture and release of hydrogen blended natural gas and concluded that the concentration of hydrogen in the gas mixture directly affects the spontaneous combustion of hydrogen due to leakage from the pipeline (*134*). Kim *et al.* conducted numerical quantitative risk assessment of gas leak from transmission pipeline carrying hydrogen blended natural gas and concluded that as hydrogen concentration in the gas blend increases so does individual risk adjacent to the pipeline, but it decreases for far fields (*135*). The crossover appears at distance between 50 and 100 m (164 and 328 ft) from the source, depending on test parameters used. Zhou *at al.* investigated diffusion of hydrogen blended natural gas leak in semi-confined space on an urban street through 3D CFD modeling (*136*). The study revealed that an increase in hydrogen concentration in the gas blend results in an increased higher maximum explosion overpressure[17]. When the hydrogen blending concentration rises from 0% to 40%, the maximum explosion overpressure increases 2.3 times, however maximum explosion overpressure grows by 21.3 times as the hydrogen blending ratio increases from 40% to 100%. The maximum explosion overpressure changes from 0.2 kPa (0.029 psi) to 8.5 kPa (1.23 psi) as hydrogen blended concentration increases from 0% to 100%.

A number of studies have investigated jet fires resulting from hydrogen blended natural gas release through experimental work. Experimental investigation of jet flames from hydrogen blended natural gas was conducted by Kong *et al.,* at varying concentrations of hydrogen blended in methane at pressures of 200 Pa to 800 Pa (*137*). The study found that lift-off height[18] and flame length decrease, while flame temperature increases as the hydrogen concentration in the gas blend increases. At the maximum hydrogen concentration of 50%, the reduction in flame length is 13.7%.

Dinkov *et al.* experimentally simulated a leak from a gas line in a domestic residence with a hydrogen-methane gas blend at hydrogen concentrations of up to 40% (*138*).

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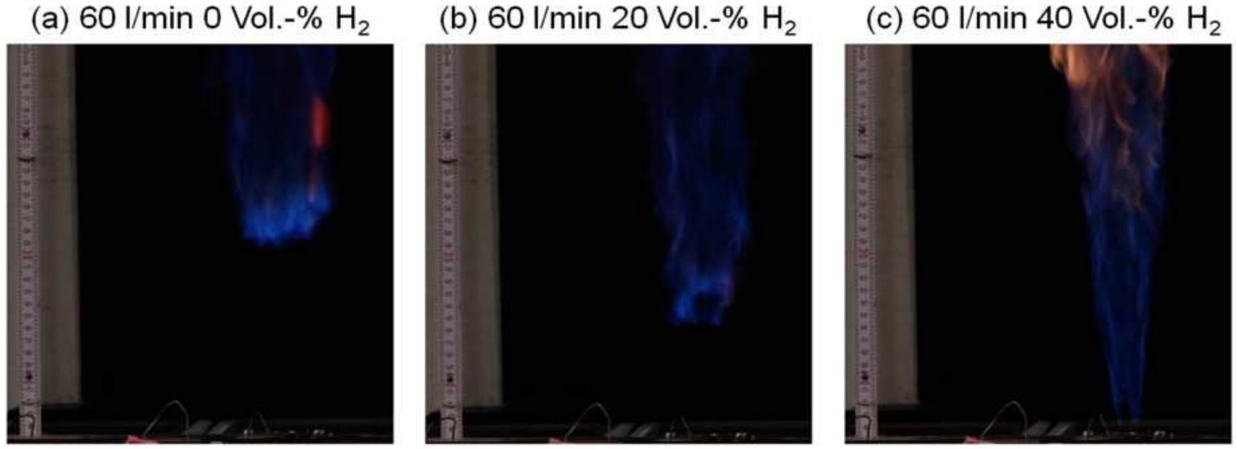
[16] The area where the concentration of released flammable gas in air is within the lower and upper flammable limits.

[17] The maximum pressure caused by a shock wave resulting from an explosion.

[18] The distance between the nozzle and the base or starting point of the flame.

The investigation into the jet fires at different concentrations of hydrogen in the gas mixture revealed that flame length increases while lifting height decreases with increasing hydrogen concentration as shown in the photos in Figure 34. The increase of flame length with increasing concentration of hydrogen, contrary to other reports, was attributed to smaller decrease in the total length from nozzle to flame tip compared to the decrease of lifting height.

Figure 34: Lift-off heights of jet flames from hydrogen-methane blends (*138*)



Liu *et al.* conducted experiments to study the properties of jet flames of 20% hydrogen blended natural gas from circular and slit type nozzles at different flame angles, different nozzle diameters, and different gas flow rates (*139*). It was revealed that the flame height of vertical jet flames rises as the nozzle equivalent diameter and heat release rate increase. The flame horizontal projection length for upward-tilted jet flames reduces with increasing tilt angle and rises with heat release rate and nozzle equivalent diameter.

An experimental study conducted by He *et al.* evaluated the effects of hydrogen addition to methane on free and wall type jet fires (*140*). The study revealed that the addition of hydrogen led to an increase in vertical temperature of the diffusive jet flame.

Kong *et al.* conducted a large-scale experimental study of jet fires of hydrogen blended natural gas, at hydrogen concentrations from 0% to 100%, at pressures between 1.6 to 4 MPa (232 to 580 psi) (*141*). Results revealed that when the hydrogen concentration of the gas blend rises from 0% to 20% the flame length of the jet fire decreases by 5%.

CHAPTER 3: Hydrogen permeation through polymeric materials

One of the challenges in adopting hydrogen blended natural gas lies in hydrogen permeation behavior through common polymer materials employed in natural gas pipeline systems. Hydrogen has a higher permeation rate through polymeric materials due to its smaller molecular size compared to natural gas that should be taken into consideration.

Studies on the hydrogen permeability of polymers have revealed varying permeability rates depending on the structure and properties of these materials. Table 6 lists the relative permeation rates of hydrogen in common polymeric materials (*19*). Table 7 shows a comparison of permeation rates of hydrogen and methane in three thermoplastics used in pipelines in the gas distribution network (*55*).

Table 6: Hydrogen permeability of various plastics at room temperature (*19*)

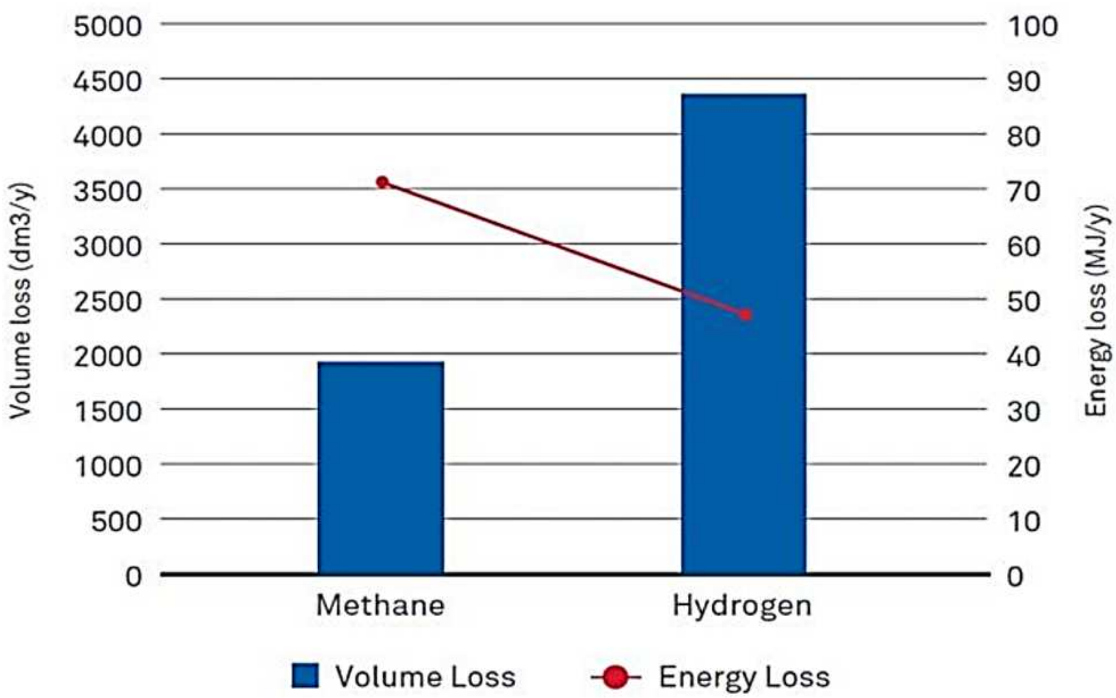
Plastics	**H_2 Permeability mol/(m·s·Pa)**
Low-density polyethylene	$1.33 – 2.84 \times 10^{-15}$
High-density polyethylene	$4.93 – 9.25 \times 10^{-16}$
Epoxy	$1.71 – 4.05 \times 10^{-16}$
Polypropylene	1.38×10^{-14}
Poly methyl methacrylate	1.24×10^{-15}
Poly vinyl alcohol	5.02×10^{-18}
PVA+ glutaraldehyde	2.81×10^{-18}
Poly vinyl chloride	8.17×10^{-16}
Poly vinylidene chloride	1.60×10^{-17}
Poly vinyl fluoride	1.8×10^{-16}
Polystyrene	7.58×10^{-15}
Polytetrafluoroethylene	3.20×10^{-15}
Fluorinated Polyimides	$1.60 – 36.2 \times 10^{-15}$

Table 7: Comparison of permeation rates of hydrogen and methane in thermoplastic materials (*55*)

Pipe Material	Permeation rate of hydrogen gas mol/(m·s·Pa)	Permeation rate of methane gas mol/(m·s·Pa)
high-density polyethylene	9.2×10^{-16}	3.2×10^{-16}
medium-density polyethylene	3.1×10^{-15}	1.4×10^{-15}
polyamide 11	4.7×10^{-16}	2.6×10^{-17}

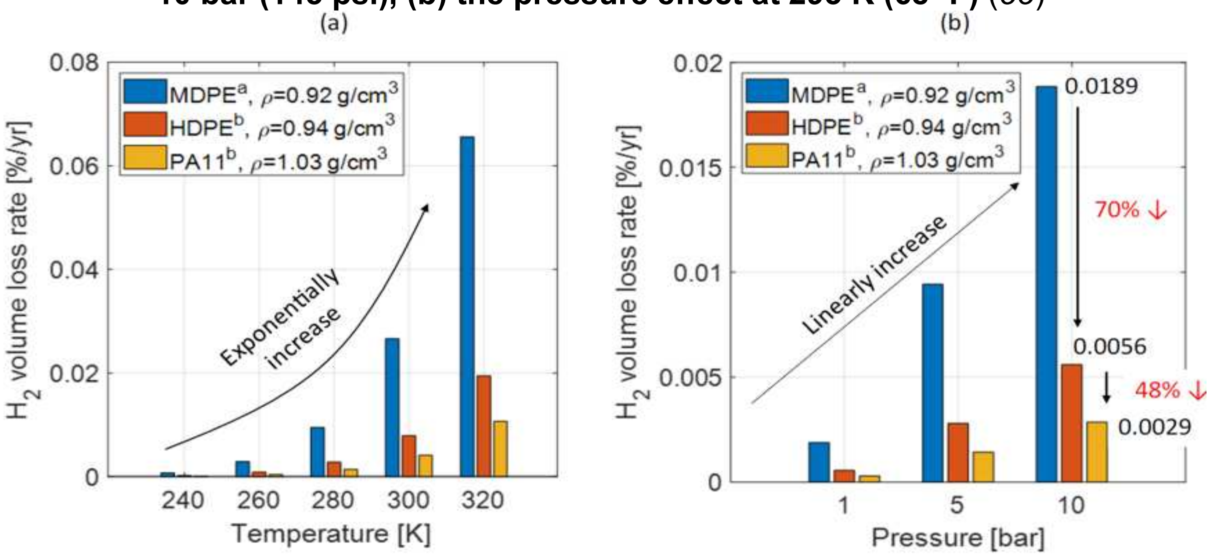
Polymeric materials are widely used in distribution pipelines, as well as in seals and gaskets (*20*, *142*). Hydrogen having a small molecular structure exhibits high diffusion rates within polymer matrices, whereas methane has relatively lower permeation rates due to its larger molecular structure (*20*). The bar chart in Figure 35 compares the calculated volume loss in dm^3/year (0.0353 cf/year) and calculated energy loss of MJ/year (948 BTU/year) for methane and hydrogen, due to permeation through a 1 km (0.62 mi) long and 90 mm (3.54 in) diameter high-density polyethylene (HDPE) pipeline operated at 2 bar (29 psi) (*4*). While hydrogen shows a higher volume loss due to its lower density, the energy loss is lower compared to methane.

Figure 35: Volume and energy loss from permeation through a HDPE pipeline for methane and hydrogen (*4*)



Simmons *et al.* estimated hydrogen loss from the US natural gas infrastructure assuming gas pipes are IPS6[19], DR11[20] with outside diameter of 168.3 mm (6.63 in), wall thickness of 15.29 mm (0.60 in), and a total cumulative length of 2.4 × 10^6 km (1.49 × 10^6 mi) (*55*). Figure 36 (a) shows percent hydrogen loss in medium-density polyethylene (MDPE), HDPE, and polyamide 11 (PA11) pipes, as a function of temperature, where ρ indicates the density for each. Figure 36 (b) shows percent hydrogen loss in MDPE, HDPE, and PA11 pipes, as a function of pressure. Under the highest service temperature of 320 K (116 ˚F) and highest service pressure of 10 bar (145 psi), the hydrogen volume loss rate in MDPE, HDPE, and PA11 are 0.066%, 0.019%, and 0.011% per year (*55*).

Figure 36: Hydrogen gas volume loss rate per year, (a) the temperature effect at 10 bar (145 psi), (b) the pressure effect at 293 K (68 ˚F) (*55*)



In recent years, there has been an increased focus on polymeric materials with low hydrogen permeability, which could be employed as coatings or liners on high strength materials used in gas storage and transportation, whose properties could be negatively impacted with hydrogen exposure. One of the common sealing components in gas systems are gaskets made of synthetic rubber materials. Zhou *et al.* conducted an experimental hydrogen permeation study for nitrile butadiene rubber (NBR) employing finite element modeling to explore the effect of filler properties on the microstructure, hydrogen permeation behavior, and hydrogen concentration distribution in NBR (*143*). The results showed that the crosslink density of NBR filled with carbon black (NBR-CB)

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[19] Nominal diameter of pipe in inches.

[20] Dimension ratio of pipe wall thickness to its outer diameter.

and silica (NBR-SC) is directly related to the filler content. NBR with higher filler content exhibited a lower hydrogen permeation coefficient and superior hydrogen barrier properties.

Lee *et al.* have investigated the enhanced gas barrier properties and injection moldability of an ethylene propylene diene monomer (EPDM) rubber-reinforced polyamide 6/ethylene vinyl alcohol (PA6/EVOH) composite for hydrogen tank liners (*144*). The authors utilized a blend of PA6 and EVOH as the matrix to achieve high hydrogen gas barrier properties. Additionally, they incorporated EPDM rubber to improve the mechanical properties and processability. As a result, the new material system displayed a 28% reduction in hydrogen permeability and an 11% improvement in tensile strength compared to a commercial material.

With regards to polyethylene (PE) materials, Lee *et al.* investigated gas permeation in low-density polyethylene (LDPE), ultra-high-molecular-weight polyethylene (UHMWPE), and HDPE when exposed to pure gases (H_2, He, N_2, O_2, and Ar) (*145*). Their findings established that gas permeation follows Henry's law, and they demonstrated how the amorphous phase of polyethylene affects permeability, showing suitability for gas barrier applications.

In another study, Lei *et al.,* fabricated and tested polyvinyl alcohol (PVA) and poly(ethylene glycol) diglycidyl ether (PEGDGE) crosslinked films for hydrogen permeability (*146*). These crosslinked films showed great potential as inner coatings to prevent hydrogen embrittlement.

Katsivalis *et al.* focused on mechanical loading effects on hydrogen permeability in thin-ply composites (*147*). The authors conducted experiments on hydrogen permeation and diffusivity in cross-ply laminates, both before and after applying tensile stress. Using Scanning Electron Microscopy (SEM), they identified defects like micro-cracks that could affect permeability. Despite mechanical loading, the thin-ply composites maintained acceptable hydrogen barrier properties.

A study by Dong *et al.* focused on PA6 used in Type IV hydrogen storage cylinders, comparing it with PA11 and HDPE (*148*). They showed that hydrogen permeability increases with temperature but decreases with pressure. Among the materials tested, PA6 had slightly better hydrogen permeation resistance compared to PA11, while HDPE showed the lowest resistance.

Li *et al.* provided a comprehensive review of the mechanisms and evaluation methods for hydrogen permeation barriers, focusing on different materials like metals, alloys, and polymers (*149*). They concluded that polymer composites reinforced with graphene show promise due to their cost-effectiveness, scalability, and improved permeation resistance. *Li et al.* also conducted a review on hydrogen permeation tests on polymer liner materials used in hydrogen storage systems, where the authors compared various testing standards and methods (*150*).

Molecular simulations by Atiq *et al.* focused on polymer pressure-volume-temperature data and hydrogen sorption (*151*). Their simulations showed that gas sorption in crystalline regions is negligible and that retention of the amorphous phase between crystals causes a significant increase in density and a decrease in sorption capacity.

Kumar explored the role of polymeric liners in hydrogen permeation behavior using finite element modeling (*152*). Through simulations, they estimated the role of structural properties and operational parameters of plastic liners in hydrogen transport properties and calculated the effective thickness required to maintain the permeation limit.

Benrabah *et al.* developed a finite element-based numerical model to predict hydrogen permeation through blow-molded plastic liners (BMPL) used in compressed hydrogen storage tanks (*153*). The model was integrated into the BlowView software to optimize liner thickness, reduce weight, and ensure adequate permeation performance. Their research highlighted the impact of material properties and thickness distribution on hydrogen permeation rates, which forms the foundation for safer and more efficient liner designs.

Su *et al.* comprehensively investigated the hydrogen permeability of PA6 used as a liner material in compressed hydrogen storage tanks through molecular dynamics simulations (*154*). The researchers examined the dissolution and diffusion behaviors of PA6 under service conditions in the temperature range 233 to 358 K (-40.3 to 184.7 °F) and a pressure range of 0 to 87.5 MPa (0 to 12691 psi). The study demonstrated that as temperature increases, both diffusion and permeability coefficients increase, while the solubility coefficient decreases. Additionally, it was found that as pressure increases, the diffusion and permeability coefficients slightly decrease, although this effect is not as significant as that of temperature. The authors evaluated the hydrogen barrier properties of PA6 and its applicability as a liner material for Type IV hydrogen storage tanks.

Zhang *et al.* reviewed the material challenges in building a green hydrogen ecosystem, highlighting the role of advancements in material science across production, storage, and application (*155*). They highlighted the potential of graphene-reinforced composites and catalytic materials to overcome the current limitations of efficiency, safety, and cost in hydrogen technologies. Building on this foundation, Fang and Ji used molecular simulations to investigate hydrogen permeation behavior in liner polymer materials for Type IV storage vessels (*156*). Their study showed that polyamide outperformed polyethylene in hydrogen permeation resistance under various temperatures and pressures.

Zhao *et al.* used coarse-grained Monte Carlo and molecular dynamics simulations to examine hydrogen solubility in polyethylene matrices (*157*). They found that the crystalline phase of polyethylene reduces hydrogen solubility, with solubility mainly occurring in the amorphous phase. In addition to these findings, Kanesugi *et al.* developed a high-pressure hydrogen permeability model for crystalline polymers such as LDPE, HDPE, and PA11 (*158*). Their model successfully predicted the pressure dependency of hydrogen permeability, which decreased as pressure increased, making the model particularly useful for high-pressure environments of up to 90 MPa (13053 psi).

The findings of Zheng *et al.* emphasized that temperature plays a crucial role in hydrogen permeability through polyethylene pipelines, as their molecular dynamics simulations revealed that hydrogen solubility and diffusion coefficients increase with temperature, while pressure has a minimal effect (*159*).

CHAPTER 4: Impact of hydrogen blending on heating value and end-use equipment

A broad variety of studies, articles, demonstrations, and evaluations have been conducted to aid in determining end-use impacts resulting from hydrogen and natural gas blends. In-service end-use equipment currently ranges from industrial turbines, furnaces, and boilers to residential heaters, cooktops, boilers and ovens. Decades of technology evolution, deployment, operations, and industry advancements have created reliable and consistent operation of end-use appliances based on traditional gas supplies with consistent gaseous properties. Manufacturers of end-use equipment design within a range of Wobbe Indices for energy content and anticipated fluid/density performance characteristics. Additionally, the thermal combustion process for natural gas appliances is impacted as hydrogen concentrations affect combustion temperatures, flue gas composition, and flow. This chapter reviews the recent literature for end-use appliances and summarizes findings associated with design, deployment, operation and performance when operating on natural gas hydrogen blends.

Heating value, combustion, and physical properties influenced by hydrogen and natural gas blends

Several experimental and demonstration efforts have evaluated the feasibility of blending hydrogen and natural gas and the related physical, energy, and combustion properties. The impact to end-user applications depends on the concentration of hydrogen blended in natural gas, but generally increases with increasing hydrogen centration. The molecular size, mass, density and combustion energy of hydrogen become more influential as conveyance pressures and flow increase. Table 8 compares the gaseous combustion properties of pure hydrogen against natural gas (*160*). Considering pure hydrogen, the broader flammability limits and lower ignition energy create additional safety concerns for locations with limited or reduced ventilation (*6*, *161*, *162*). However, the properties of hydrogen-natural gas blends and the associated combustion characteristics are different from that of pure hydrogen and are dependent on the percentage of hydrogen in the blend. In a gas mixture of natural gas and hydrogen flame speed and flame temperature increase with increasing concentration of hydrogen, while the Wobbe Index[21] (WI) decreases to a minimum as hydrogen

[21] A measure of interchangeability of different gaseous fuels in terms of energy output. It is defined as the ratio of the calorific value (higher heating value) of a gas to the square root of its specific gravity.

concentration increases from 0% to 85%, and increases as concentration increases from 85% to 100% (*3*).

Table 8: Natural gas and hydrogen combustion properties (*160*)

Parameter	Natural Gas	Hydrogen
Relative Density (air=1)	0.55	0.07
Flammability limits (Mol %)	4.4 – 17	4.4 – 77
Ignition energy (mJ)	0.26	0.0017
Combustion energy (MJ/m^3)	38	13
Wobbe number (MJ/m^3)	48-54	41
Flame colour	Blue	Colourless
Molecular mass (g/mol)	16	2
Molecule size (pm)	220	75
Infrared absorption	Yes	No
Joule-Thompson coefficient (K/bar)	0.4	-0.03
Sound velocity (m/s)	338	1203

Combustion and heating value with hydrogen and natural gas blends

Several laboratory and demonstration projects have evaluated specific commercial or residential end-use appliances operating on hydrogen and natural gas blends. The specific appliance design and components can vary by manufacturer and region. Due to these variances, it cannot be presumed that results from a specific boiler, oven, cooktop, or furnace are applicable across all models, regions, or conditions.

The HyTest project evaluated six condensing residential burners, commonly utilized in western Europe, in a controlled laboratory setting (*100*). To establish the calorific value of each gas mixture, the gas flow rate to the boiler was measured along with the water flow rate and the change in temperature through the boiler. The stated heat to water ratio was estimated using the entrance and outlet temperature of the water in the boiler. The calorific value of the gas was found as the heat transferred to the water divided by the volume of gas combusted. The HyTest project demonstrates an approximate 15% drop in gross calorific value (GCV) using the 20% hydrogen blend compared with the natural gas (*100*). The drop in GCV is expected based on the natural gas and hydrogen combustion properties.

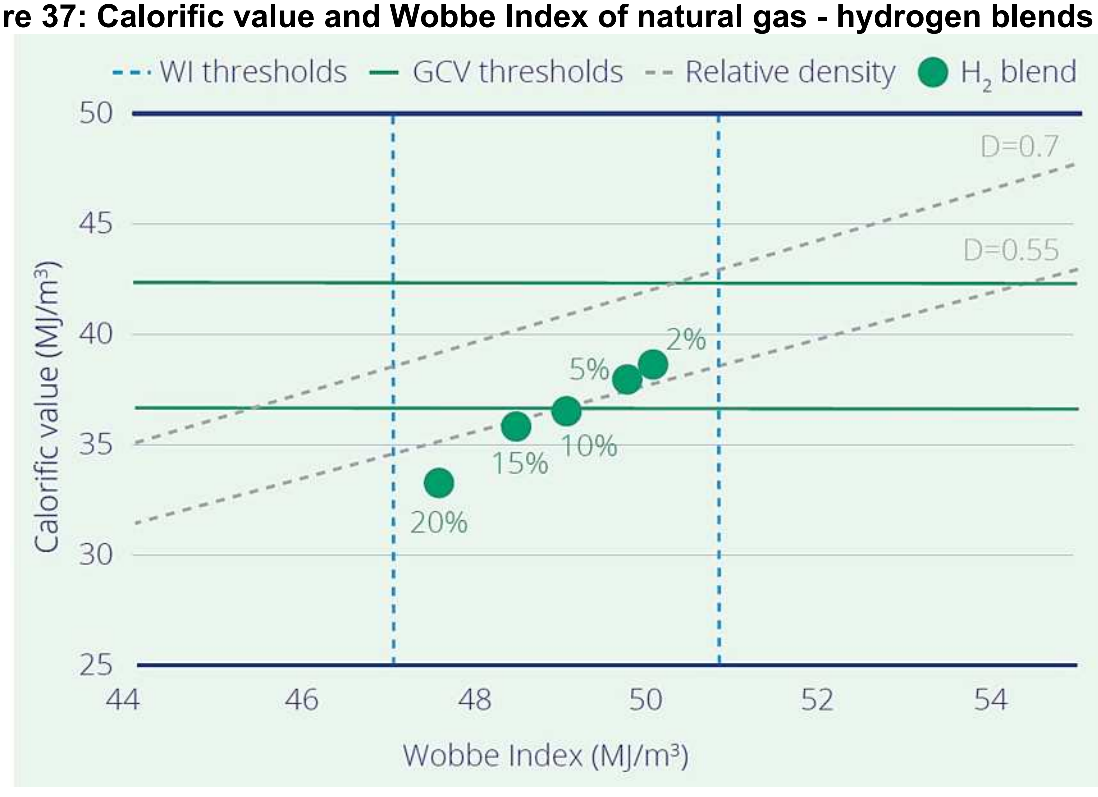
The Wobbe Index and GCV for the different blends are shown Figure 37 relative to the Gas Quality Specification in the Irish Code of Operations which requires the WI of natural gas at entry points to be between 47.2 and 51.4 MJ/m^3 (1266.8 and 1379.5

BTU/cf) (the vertical dash lines in Figure 37). Hydrogen blends were tested from 2% to 20%. The Irish Code of Operations requires a GCV between 36.9 and 42.3 MJ/m^3 (990.4 and 1,135.3 BTU/cf) Blends of 10% hydrogen and above were found to be below the lower GCV threshold (*100*).

Sorgulu *et al.* investigated experimentally the combustion performance of hydrogen-natural gas blends by evaluating the effects of hydrogen addition in varying volumetric fractions (10%, 20%, and 30%) on gas consumption, heating time, and lower heating values (*163*). Their findings indicate that a 20% hydrogen blend led to a 7.99% reduction in natural gas consumption but also increased heating time by 15.87%.

Yang *et al.* evaluated numerically the energy-saving potential and thermal performance of a hydrogen-enriched natural gas fired condensing boiler (*164*). Their analysis considered hydrogen blending ratios of 10%, 20%, and 30% and used a condensing boiler with a nominal thermal power of 35 kW (119,425 BTU/hr). They found that hydrogen blending increases the boiler's thermal efficiency by up to 8.8% and reduces carbon dioxide emissions by 55.4%. Additionally, they found that the existing condensing boiler designs common in Europe can meet heat recovery requirements even with 100% hydrogen enrichment. The condensing boilers evaluated utilize flue gas heat exchangers to improve thermal efficiency and are less common in traditional California residential applications.

Figure 37: Calorific value and Wobbe Index of natural gas - hydrogen blends (*100*)



Tong *et al.* analyzed the feasibility of hydrogen injection into natural gas pipelines in Zhejiang, China, focusing on maintaining gas quality while achieving carbon neutrality (*165*). Using data from various gas sources in the region, they calculated the calorific value, Wobbe Index, and other critical parameters for hydrogen-natural gas blends under simulated conditions. The study concluded that the hydrogen mixing ratio should be carefully managed, with limits set at 10% for long-distance pipelines and 20% for urban pipelines, to meet gas quality requirements without compromising pipeline performance.

Flame characteristics and combustion models for hydrogen and natural gas blends

A number of articles in the literature utilize numerical and combustion models, chemical kinetics, and other techniques to characterize the combustion of hydrogen-natural gas blends. The majority of the publications focus on the resulting emissions from hydrogen blended gas combustion. These publications have a high relevance for specific conditions and specific operations.

Du *et al.* conducted both experimental and numerical analyses to investigate the combustion behavior of hydrogen-blended natural gas in swirl burners (*166*). The study specifically evaluated hydrogen blending ratios of 10% and 20% by volume to analyze their impact on combustion dynamics. They examined how variations in swirl angle and swirl length impact flame temperature, combustion stability, and pollutant emissions. The results showed that increasing the swirl angle and swirl length improved combustion efficiency while reducing carbon monoxide and nitric oxide (NO) emissions, with the optimal performance observed at a swirl length of 12 mm, which reduced nitric oxide emissions by 36.11%.

Li *et al.* performed numerical simulations to investigate the combustion behavior of a natural gas-hydrogen blend in a partially premixed gas-fired boiler (*167*). Their study focused on the impact of varying hydrogen blending ratios (0%, 10%, 20%, 30%, and 40%) on combustion stability, NO_X emissions, and overall thermal performance. Combustion stability was evaluated through indicators such as the uniformity of temperature distribution and the absence of pressure fluctuations. The researchers observed that higher hydrogen blending ratios led to increased combustion temperatures, which, while enhancing thermal efficiency, also raised the potential for NO_X formation. At 10% hydrogen concentration NO_X emissions increase 14.7% compared to pure methane, at 20% blending concentration there is an additional 2.5% increase, while at 30% blending concentration NO_X emission increase additionally 47.3%. Their results indicated that maintaining the hydrogen blend ratio below 20%

helps reduce NO_X emissions and ensures combustion stability, while higher hydrogen blend ratios lead to increased combustion temperatures.

Dong *et al.* explored the chemical kinetics and the effects of various hydrogen blending ratios on the reactions of natural gas (*168*). Using CHEMKIN-PRO software and the GRI-Mech 3.0 mechanism, they simulated the blending of hydrogen with natural gas to assess its potential to reduce carbon emissions such as carbon monoxide and carbon dioxide (CO_2). The results demonstrated that increasing the blended hydrogen concentration from 0% to 50% enhances combustion efficiency, reduces the duration of reactions, and significantly lowers carbon monoxide and carbon dioxide emissions (*168*). Similarly, Pan *et al.* explored three different kinetic models to examine the impact of hydrogen blending on NO_X formation in natural gas systems, at 0%, 25%, 50%, 75% and 100% hydrogen concentration (*169*). They found that as hydrogen content increased from 0% to 50%, NO_X emissions increased. As hydrogen content increased beyond 50%, NO_X emissions decreased, as thermal NO_X was suppressed.

Zhao *et al.* employed a CFD model to investigate the co-firing of hydrogen and natural gas in a practical dry low NO_X combustor model for gas turbines (*170*). The study aimed to understand the impact of increasing hydrogen content from 0% to 90% on flame behavior and NO_X emissions. The results indicated that as the hydrogen concentration increased, the flame length shortened, and NO_X emissions rose, with hydrogen concentration increasing up to 60%. A drop of NO_X emissions was observed at hydrogen concentration of 70%, followed by an increase in NO_X emissions at 80% concentration.

Breer *et al.* conducted numerical studies on hydrogen-methane mixtures and found that hydrogen addition reduced NO_X emissions under typical gas turbine combustion durations, with the main NO_X production arising from post-flame thermal mechanism (*171*). The study emphasized that hydrogen kept NO_X levels lower compared to methane, particularly under high-pressure conditions. Lopez-Ruiz *et al.* conducted a CFD study on an industrial reheating furnace burner, focusing on flameless combustion[22] using hydrogen-natural gas blends (*172*). They evaluated the use of these blends under different proportions (0%, 23%, 50%, and 75% hydrogen) to analyze their impact on NO_X emissions and the overall combustion process. The results showed that the burner was capable of maintaining flameless combustion with stable temperatures and low NO_X emissions, even with higher concentrations of hydrogen, making it a viable option for decarbonizing industrial processes.

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[22] The chemical reaction of combustion without flame.

Xu *et al.*, applied the staged MILD (Moderate or Intense Low-oxygen Dilution) combustion strategy to methane-hydrogen mixtures in a reactor network model. The authors found that this approach significantly reduced NO_X emissions in hydrogen-enriched mixtures, achieving up to 67.4% NO_X reduction efficiency relative to the baseline of conventional MILD combustion without fuel or air staging (*173*). Similarly, Xu *et al.* investigated the effects of hydrogen-enriched methane at 0%, 25%, 50%, 75%, and 100% hydrogen concentration, on MILD combustion and found that hydrogen extended the MILD combustion limits, making it sustainable at lower wall temperatures (*174*). Their results also indicated that as hydrogen levels increased, NO_X formation pathways shifted, with hydrogen playing a significant role in nitric oxide reduction at lower temperatures. In line with this, Cecere *et al.,* analyzed the effects of exhaust gas recirculation (EGR) and hydrogen mixing ratios on NO_X emissions in methane-hydrogen-air mixtures under a 25 bar (362.6 psi) pressure (*175*). Their simulations demonstrated that while hydrogen increased NO_X formation, EGR effectively reduced flame temperatures, mitigating NO_X and CO_2 emissions.

Swaminathan *et al.,* developed a two-step numerical model to analyze the effects of hydrogen-enriched fuel on NO_X emissions in an industrial burner (*176*). The model successfully reduced NO_X emissions by varying the air mass flow ratio. In terms of the effect of hydrogen concentration natural gas, while it rose from 0% to 50%, nitric oxide emissions increased by 41.8%, while carbon monoxide emissions decreased by 76.8%. These findings highlight the effectiveness of hydrogen in reducing carbon monoxide emissions, although the rise in NO_X emissions should be addressed using appropriate strategies. Similarly, Saleem *et al.,* developed a simple linear model and an artificial neural network (ANN) model to predict NO_X emissions from fuels such as ammonia, natural gas, hydrogen, and kerosene (*177*). Their modeling analysis results showed that NO_X emissions increase significantly with increasing hydrogen blending concentration. For example, NO_X emissions exceeded 2000 ppm when hydrogen dominated the gas blend composition (greater than 50%).

Combustion emissions for hydrogen and natural gas blends

Several projects reported reduced CO_2, carbon monoxide and NO_X concentrations in gas emissions from residential boilers using 20% hydrogen blends (Table 9). THyGA and the HyTest projects recorded comparable NO_X emission reductions of 43% and 40% (*100*, *178*). The CO_2 reduction recorded was also similar at about 12%, while this number for the HyDeploy 2 project is 16% (*83*). In addition, the HyTest and THyGA projects reported a reduction in carbon monoxide by 37% and 42%, respectively. The energy density on volumetric basis of a mixture of 20% hydrogen in natural gas is roughly 14% less than that of just natural gas. Based on this energy density reduction, the CO_2 emissions from a gas mixture with an energy content equivalent to natural gas is estimated to be roughly 7% less than the CO_2 emissions from natural gas (*100*).

Table 9: Emissions reductions measured using 20% hydrogen blend (*100*)

20% H_2 blend compared to natural gas	CO_2 reduction	CO reduction	$CO:CO_2$ reduction	NOx reduction
HyTest (Gas Networks Ireland and UCD)	11.8%	37.2%	43%	40%
HyDeploy	16%	28%	32%	22%
THyGA report	decrease	42%	~39%	43%
H_2NG report	12%	20%	~15%	57%

Basinger *et al.* conducted an experimental study to evaluate the performance and emissions of residential boilers running on natural gas and hydrogen blends (*179*). They tested 39 different boilers with varying hydrogen blend ratios and found that low-NO_X water heaters could tolerate up to 70% hydrogen without modification, while conventional devices could handle 40% to 50%. Additionally, they observed that as the hydrogen ratio increased, NO_X emissions decreased.

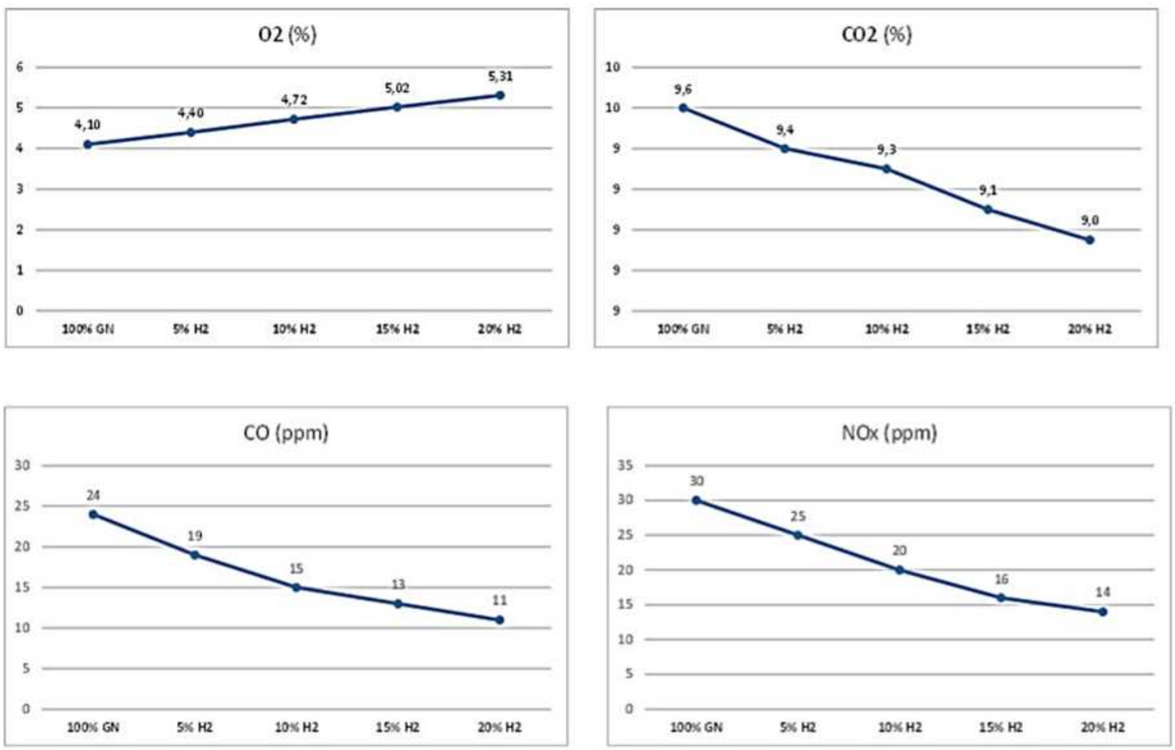
Zhan *et al*. investigated the effects of hydrogen blended natural gas on the combustion stability and emissions of a boiler burner (*180*). They developed a test system to assess the changes in flame shape, burner temperature, and pollutant emissions under various hydrogen blending ratios and heat loads. The results demonstrated that increasing the hydrogen ratio improved combustion stability and reduced carbon monoxide emissions, while the NO_X emissions showed a mixed response depending on the hydrogen ratio and heat load. The optimal hydrogen blending ratio for safe operation was identified as 40% under the study conditions.

Soroka *et al.* investigated the substitution of natural gas with methane-hydrogen mixtures in household gas-powered appliances, specifically a heating boiler and a gas stove (*181*). The experiments involved testing methane mixtures with 0%, 5%, 20%, 30%, and 50% hydrogen content and assessing the energy efficiency and emissions of pollutants such as carbon monoxide and NO_X. The results showed that the boiler's efficiency increased with higher fuel flow rates, while the gas stove showed an efficiency peak followed by a decrease as heat capacity increased. Additionally, environmental emissions from the stove burner in terms of carbon monoxide and NO_X emissions decreased with increase of hydrogen concentration.

Ozturk *et al.* conducted an experimental investigation to assess the emissions impact and performance of burning hydrogen-natural gas blends with hydrogen concentration of 10%, 20%, and 30% in gas stoves (*182*). They measured the emissions of carbon dioxide, carbon monoxide, and NO_X under different hydrogen blending ratios and also performed a life cycle analysis to evaluate the environmental effects. The results indicated that raising the hydrogen blending ratio enhanced the combustion efficiency and lowered carbon dioxide emissions, while NO_X emissions fluctuated, they were lower for all three gas blends compared to the natural gas alone.

Nortegas has performed case studies for commercial steam boilers and heat treatment furnaces (*60*). The case study modeling evaluation determined hydrogen percentages up to 30% required no modifications of the commercial burners and thermal performance remained unaltered. Nortegas has conducted emissions measurements for boiler operation from 0% to 20% hydrogen concentrations (Figure 38).

Figure 38: Nortegas emissions measurement results for boiler operations at 0%, 5%, 10%, 15%, and 20% hydrogen blending concentration (*60*)



Liu *et al.* conducted experimental testing on a domestic gas cooktop using a blend of 80% natural gas and 20% hydrogen to assess its thermal performance, heat transfer efficiency, and emissions (*183*). They found that hydrogen blending increased the gas flow rate, decreased thermal input by 7.94%, and reduced carbon monoxide emissions, while NO_X emissions slightly increased from 13.5 ppm to 13.7 ppm. The study also optimized the gas cooktop by lowering the wok stand height, which improved heat transfer efficiency and reduced NO_X emissions. Based on these findings, the authors of the study suggest that physical modifications to optimize heating conditions may be advantageous for some cooking operations.

Glanville *et al*. examined the effects of hydrogen/natural gas blends focusing on partially premixed combustion designs, evaluating the impacts on NO_X emissions and operational performance (*184*). They conducted both laboratory tests and field tests at a utility-owned training facility, which simulated residential environments with typical household appliances. The hydrogen blends reached up to 30% by volume and were tested across various heating appliances, including water heaters and furnaces. The results showed a reduction in heating output of up to 11%, stable or declining NO_X emissions, and minor changes in efficiency, with a 1.2% decrease for standard NO_X burners and a 0.9% increase for ultra-low NO_X burners.

Yaïci and Entchevet used a model to investigate the performance of a domestic condensing boiler using hydrogen natural gas blends and pure hydrogen as fuel (*185*). They examined the effects of hydrogen content on combustion properties, boiler efficiency, and pollutant emissions, comparing stoichiometric and lean combustion scenarios. The results indicated that pure hydrogen combustion maximized water vapor in the exhaust and improved boiler efficiency, while lean combustion reduced pollutant emissions.

End-use equipment operations with blended fuel

The majority of literature identified for end-use applications has focused on combustion equipment and appliances. Chemical processes to generate hydrogen utilizing natural gas or methane as a feedstock are not part of this review. Additionally, stationary and mobile internal combustion engines utilizing hydrogen and natural gas mixtures have been extensively addressed in internal combustion engine and transportation literature and are also not included this review. Industrial, commercial, and residential natural gas equipment including gas turbines, furnaces, boilers, ovens, and cooktop end-uses are the most prominent literature and reporting activities covered in this section. The most relevant end-use publications are summarized below either as industrial and commercial equipment or residential appliances.

Hydrogen blending impacts on the residential appliance sector

Residential natural gas appliances typically perform space heating, cooking, water heating or a combination thereof. Residential appliances typically incorporate burner assemblies utilizing fixed orifices with potential air adjustments. Combustion air fuel (AF) mixture is typically controlled through calibrated orifices, tuned field adjustments, and/or real time monitoring of flue/combustion gas (CO_2, O_2). Fixed air mixture adjustment is either accomplished during installation or servicing; while more advanced residential burners incorporate active controllers to manage the combustion regime. Residential appliances operate at lower gas volumes and pressure with minimal user involvement in combustion monitoring. Once installed, residential users expect the appliance to perform consistently and safely regardless of the composition of the fuel delivered via the pipeline utility service.

The literature has focused on appliance performance, capabilities, reliability, safety, and emission impacts associated with hydrogen and natural gas mixtures. Previous studies and efforts have identified a variety of challenges with existing appliances operating at hydrogen percentages exceeding 50% by volume. Therefore, recent literature has focused on hydrogen blending in the 20-30% range which appears to impact some appliance functionality and operations under specific conditions. The US Department of Energy National Energy Technology Laboratory (NETL) recently completed a US based hydrogen appliance assessment report determining 20%-30% acceptability for residential natural gas appliances (*186*). The FutureGrid project demonstrations identified 20% hydrogen-natural gas blend as acceptable for end-use residential appliances in service within Great Britain (*54*).

Nortegas, a utility provider in Spain has deployed a test loop named H2SAREA to evaluate hydrogen and natural gas blending in their domestic distribution system (*60*). The H2SAREA project has demonstrated 10% blending with no observable impacts on residential service or appliance operation and safety. Nortegas has expanded the study to 15% and subsequently 20% hydrogen blending with results yet to be released.

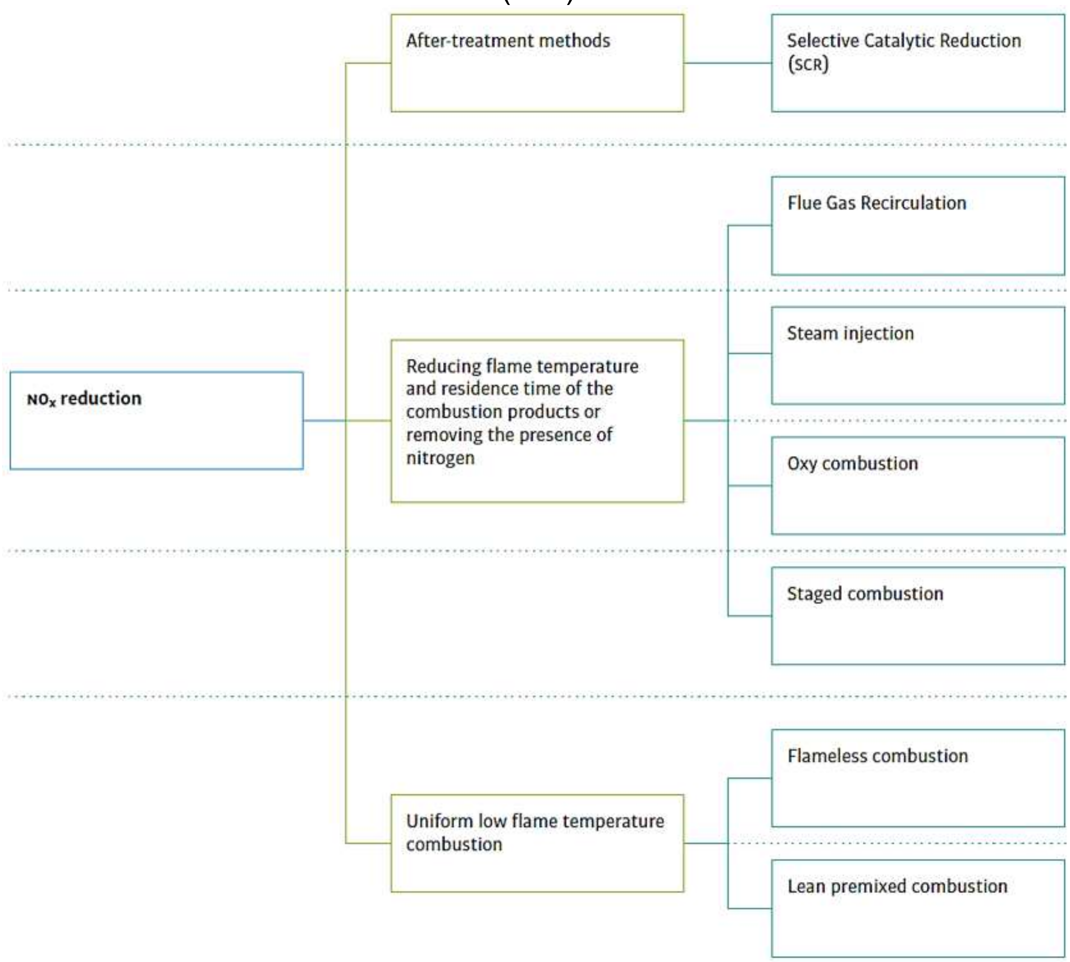
Sorgulu *et al.* examined the effect of burner head geometry on the flame dispersion and combustion performance of gas stoves using hydrogen-natural gas blends (*187*). They designed six different burner geometries and conducted experimental tests using both natural gas and a blend containing 30% hydrogen. The results demonstrated that adding hydrogen to natural gas shortened the flame height and improved combustion efficiency, with notable changes in flame color and aspect ratio depending on the burner design. Similarly, Ozturk *et al.* experimentally investigated the combustion performance of five different burner head designs in residential gas stoves using natural gas and hydrogen-natural gas blends (*188*). They found that the burner head with three lateral and two top circular holes had the shortest heating time when burning natural gas, while the burner with one lateral and three top circular holes performed best with a 30% hydrogen-natural gas blend. The study also demonstrated that hydrogen addition increased heating times due to its lower volumetric heating value.

The Hydrogen Park South Australia project demonstrated 5% renewable hydrogen mixed with distributed natural gas to 700 residential homes and associated appliances in the selected community (*84*). The project reporting found no impacts on appliance functionality, safety, and performance with confidence in operations at 10% hydrogen blending.

Hydrogen blending impacts on industrial and commercial end-use applications

Industrial and commercial gas end-use typically consists of significantly higher gas volumes with increased operating temperatures. A number of demonstration projects have evaluated the blending impacts on industrial and commercial natural gas users. The HyDelta 2.0 team reviewed proposed industrial high temperature burner mitigation technologies to reduce NO_X impacts (Figure 39) (*108*). The commercial and industrial combustion strategies incorporate modifications to the burner/combustion assemblies or significant additions to flue gas aftertreatment.

Figure 39: Industrial high temperature burner NO_X mitigation technology options (*108*)

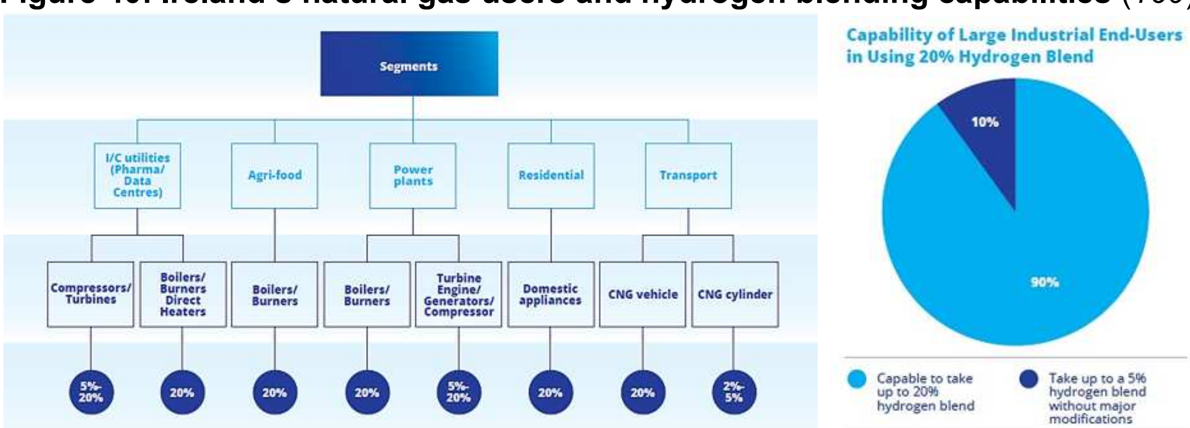


The HyDeploy 2 demonstration project evaluated a variety of industrial and commercial operations (*83*) including in commercial furnaces, kilns, ovens, and boilers with 20% hydrogen blended gas.

Giacomazzi *et al.* reviewed the combustion characteristics and barriers to the use of hydrogen in energy transition applications, focusing on hydrogen-enriched blends such as hydrogen-enriched natural gas (HENG) and hydrogen-ammonia mixtures (*189*). The study highlighted the challenges of hydrogen's high flame speed and combustion instability, as well as the reduction in carbon dioxide emissions with increased hydrogen content.

The HyEnd project team evaluated Ireland's transmission and distribution natural gas end users for integrating hydrogen blends (Figure 40) (*160*). Most end users connected to transmission and distribution gas networks did not experience any critical issues with a 20% hydrogen blend. However, gas power plants in the network are currently challenged in using a 20% blend of hydrogen with existing turbines due to concerns about NO_X emissions and combustion flame modifications. Out of the 42 major industrial users connected to the network, seven gas-fired power plants receive natural gas through the transmission network in the Republic of Ireland. Three of them can use a 5% hydrogen blend with minor modifications to their gas turbines. Three plants are exploring the use of up to 40% hydrogen blends by upgrade the combustion systems by 2030.

Figure 40: Ireland's natural gas users and hydrogen blending capabilities (*160*)



Cecere *et al.* reviewed current gas turbine combustion technologies focusing on their adaptability to hydrogen-enriched natural gas blends, including up to 100% hydrogen (*190*). They evaluated fuel flexibility, combustion efficiency, and emissions control in various gas turbine designs. The review highlighted the potential of NO_X emissions reduction technologies like dry low emission (DLE) and micro-mixing to support decarbonization efforts while reducing NO_X emissions, making them promising candidates for future hydrogen-based power generation.

Laget *et al.* explored the use of hydrogen blended with natural gas in an industrial gas turbine (*191*). Their experimental research demonstrated that up to 25% hydrogen can be safely co-fired with natural gas without requiring modifications to the turbine hardware, reducing carbon dioxide emissions by 9%. However, an increase in NO_X emissions was observed, which were shown to be controllable through combustor tuning, and at hydrogen concentration of 10% the NO_X emissions could be reduced to the same level as 100% natural gas. In a related study, Harper *et al.* conducted a hydrogen co-firing demonstration at Georgia Power's Plant McDonough using a Mitsubishi Power M501G gas turbine (*192*). The tests evaluated the impact of blending natural gas with up to 20.9% hydrogen by volume on gas turbine performance, emissions, and combustion stability. The results showed that hydrogen blending increased combustion stability, reduced carbon monoxide emissions, and demonstrated the feasibility of maintaining NO_X levels similar to natural gas operation with proper fuel control adjustments. Steele *et al.* detailed a GE turbine demonstration project conducted at a New York power generation plant that operated at 5-44% hydrogen blends by volume (*193*). The demonstration showed that selective catalytic reduction and carbon monoxide catalyst systems were able to control the stack NO_X, carbon monoxide, and ammonia slip levels below the plant's regulatory permit limits with hydrogen cofiring. Harper *et al.* demonstrated a Siemens dry low NO_X turbine operating on up to 38.8% hydrogen blend by volume (*194*). The demonstration results evaluated the effect of burner tuning, i.e. changing the fuel split to the several stages of the burners. The manual tuning reduced the NO_X emissions practically to the level of natural gas-only operation.

NETL has completed an industry review of natural gas turbine operation and performance for hydrogen combustion and resulting NO_X emissions (*186*). The report states that while attaining 100% clean hydrogen combustion in gas turbines presents difficulties, several successful initiatives have been reported by the industry. Turbines equipped with diffusion combustors show the potential for 100% hydrogen operation. However, without proper mitigation techniques, NO_X emissions can increase up to 8 times compared to natural gas combustion. For example, uncontrolled NO_X emissions from hydrogen combustion in turbines can exceed 200 ppm, significantly higher than the limits set by most air quality regulations, such as the U.S. Environmental Protection Agency (EPA) standard of 25 ppm for stationary sources. The NETL report indicates that it is probable that much of the industry will be capable of manufacturing commercial-grade turbines that can operate on pure hydrogen by around 2030 based on existing research advancements and publicly disclosed projections. These forecasts indicate that operating on blends below 100% should simultaneously become more prevalent and manageable.

Safavi *et al.* investigated through modeling the feasibility of applying combined cooling, heat, and power (CCHP) systems for commercial buildings using hydrogen-methane blend fuels (*195*). The results showed that, under the conditions evaluated, a CCHP system can deliver economic and greenhouse gas emissions benefits to electric power grids with marginal CO_2 intensities greater than 230–260 g/kWh. The authors reported that blending up to 50% hydrogen to natural gas has the potential to reduce the break-even intensity by 12%.

Wang *et al.* examined the thermal efficiency and NO_X emissions of a large-scale industrial steam boiler fueled with hydrogen-enriched natural gas, based on modeling (*196*). They proposed three different operating scenarios and evaluated the boiler's performance as the hydrogen volumetric fraction increased from 0% to 90%. The results indicated a reduction in NO_X emissions and notable variations in thermal efficiency as the hydrogen content increased.

CHAPTER 5: Potential climate and health impacts associated with hydrogen blending

This chapter focuses on modeling and analysis performed to assess the global warming potential of hydrogen, and potential health impact of hydrogen.

Global warming potential of hydrogen

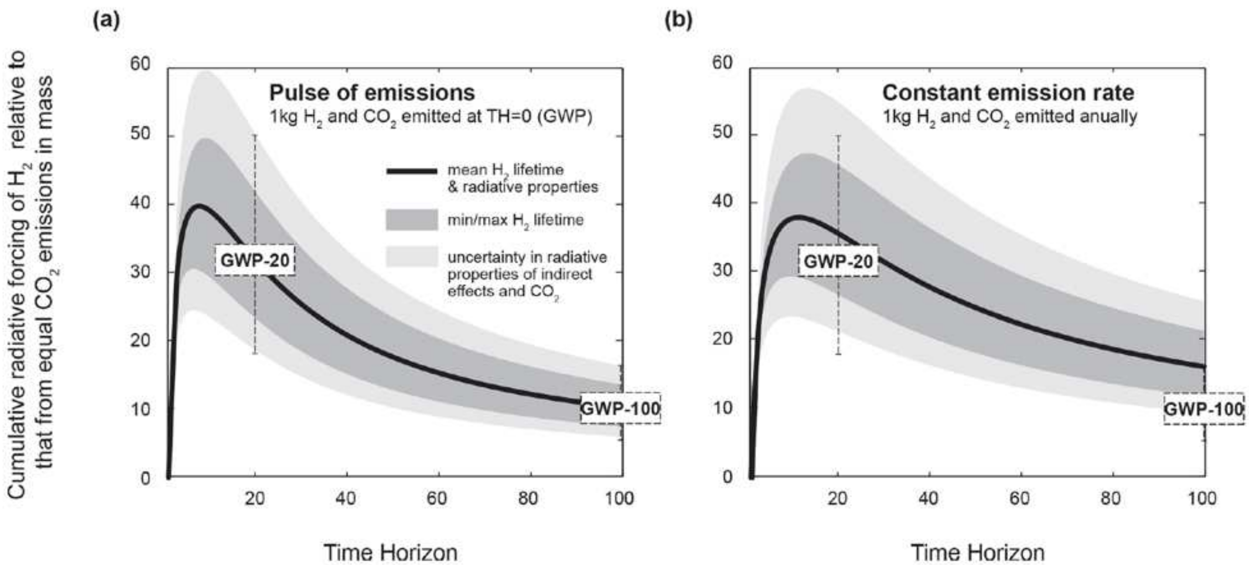
This section provides a review of articles published within the review period related to hydrogen's indirect global warming potential. Literature related to the broader greenhouse gas (GHG) reduction potential of hydrogen blending into natural gas or life cycle emission assessments of hydrogen processes and use cases are not included. Recent research has highlighted the indirect global warming potential (GWP) of hydrogen when released into the atmosphere. Hydrogen itself is not a greenhouse gas (GHG), but it influences atmospheric chemistry, prolonging the atmospheric lifetime of methane, a potent GHG (*4*, *106*, *197*). Hydrogen in the atmosphere impacts atmospheric hydroxyl radicals (OH), resulting in an increase in the lifetime of methane (*198*).

A study by Sand *et al.* utilized an aggregate of five different global atmospheric chemistry models to derive an estimate for the GWP100 of hydrogen of 11.6, with one standard deviation uncertainty of 2.8 (*199*). The uncertainty of this estimate is based on factors including photochemical production of hydrogen, soil uptake, lifetimes of methane and hydrogen, and the hydroxyl radical feedback on methane and hydrogen. The study emphasizes the importance of minimizing hydrogen emissions to the atmosphere from gas leaks, in order to achieve the desired climate benefits from future hydrogen economy.

Ocko *et al.*, assessed the atmospheric warming effects of hydrogen emissions, focusing on hydrogen's indirect impact on atmospheric chemistry (*200*). When hydrogen leaks into the atmosphere, it reacts with OH radicals, reducing their concentration and thereby increasing the atmospheric lifetime of methane. This, in combination with increased tropospheric ozone and stratospheric water vapor, results in the warming associated with hydrogen.

Findings from this study indicate that hydrogen's GWP over a 20-year period (GWP20) can be as high as 33, compared to a central estimate of 11 for the GWP over a 100-year period (GWP100). Figure 41 illustrates how hydrogen's relative warming impact changes over time compared to carbon dioxide (CO_2). It shows that hydrogen's maximum GWP occurs within the first few decades after emissions, emphasizing the importance of mitigating leakage. The results also indicate that continuous emissions of hydrogen, as opposed to a one-time pulse, lead to a higher cumulative warming effect over time, which should be taken into consideration, especially in large-scale deployments of hydrogen.

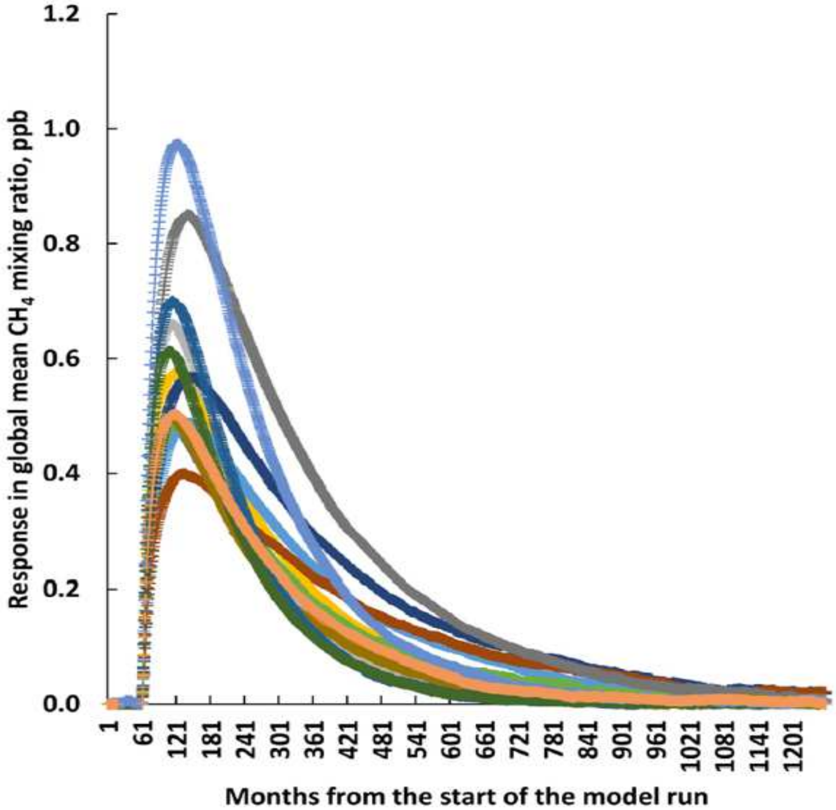
Figure 41: Warming potency of hydrogen relative to carbon dioxide using cumulative radiative forcing as a proxy for (a) a one-time pulse of equal emissions in mass and (b) a constant emission rate of both hydrogen and carbon dioxide for equal emissions in mass (*200*)



Derwent *et al.* examined the climate impacts of hydrogen emissions, focusing on its sensitivity to various factors using the TROPOS chemistry-transport model (*201*). The study assessed how hydrogen pulses of varying size, timing, and geographical distribution impact atmospheric methane and ozone concentrations. The authors used sensitivity analysis to refine the GWP range of 3.3–12.8 published in five different studies to 7.1–9.3, with a best estimate of 8 ± 2 over a 100-year time horizon. Hydrogen leakage across the supply chain indirectly contributes to global warming by depleting OH radicals, and extending methane and ozone's lifetimes. It is worth noting that the estimated GWP20 and GWP100 for hydrogen are lower than the established GWP20 and GWP100 values for methane (*202*, *203*).

Figure 42 shows the methane concentration response following a hydrogen pulse, showing a peak increase and subsequent decline due to OH depletion (*201*). It should be noted that the pulse events simulated in the articles discussed are typically meant to simulate large one time leaks, rather than emissions occurring during normal operations.

Figure 42: Methane responses to 200 Tg (2 × 10^8 US ton) pulses of hydrogen emitted during January across northern hemisphere mid-latitudes centered on 42°N in fourteen Monte Carlo replicated TROPOS model runs (*201*)



Bryant *et al.*, explored how rising atmospheric hydrogen levels affect ozone and methane concentrations under varying oxides of nitrogen (NO_X) emission scenarios (*204*). Using the UK Earth System Model (UKESM1), the study evaluates hydrogen's GWP in future scenarios where NO_X emissions are expected to decrease due to cleaner energy technologies.

The study confirms that increased hydrogen concentrations in the atmosphere lead to a decrease in OH concentrations, extending methane's atmospheric lifetime, which intensifies hydrogen's indirect warming effect. Additionally, hydrogen also promotes ozone formation through increased hydroperoxyl radical (HO_2) production. The authors found that the GWP100 of hydrogen is relatively stable across different NO_X levels, with only a slight observed decrease, suggesting that hydrogen's warming impact will persist even as NO_X emissions decline.

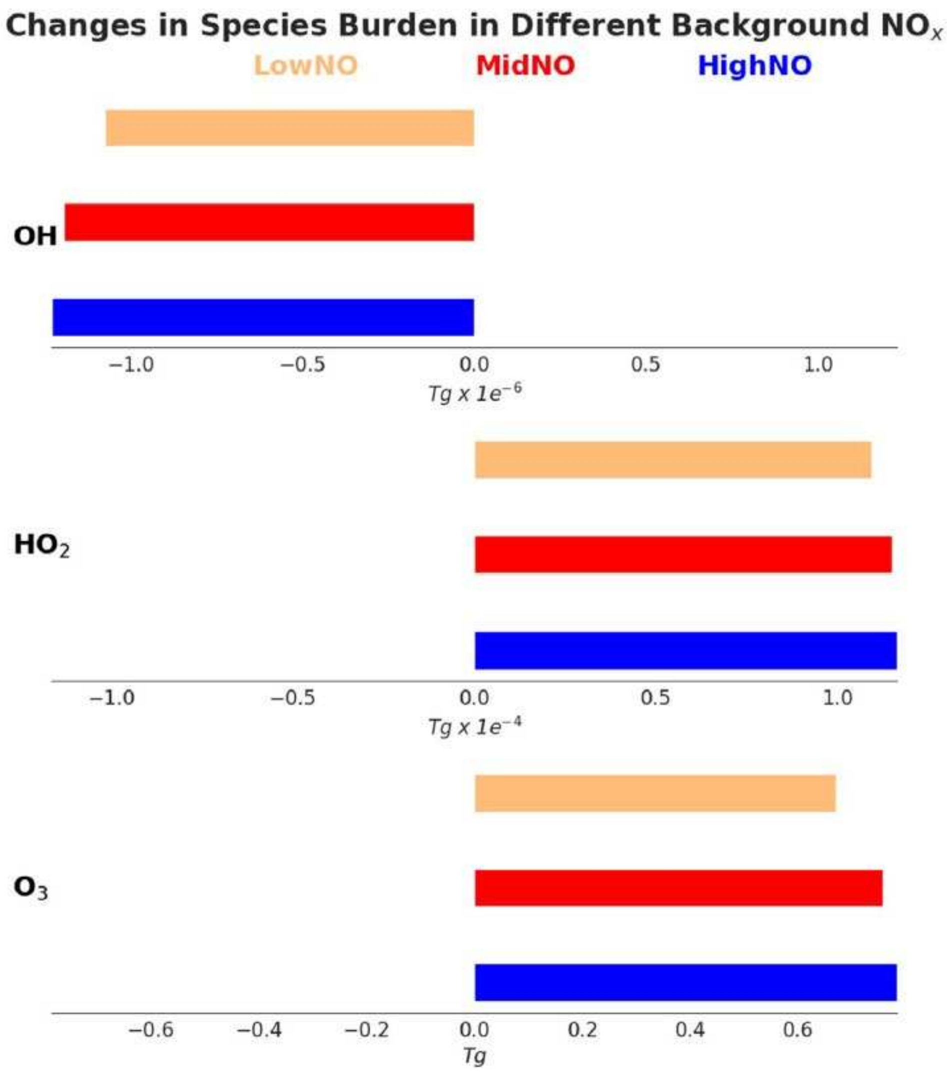
Table 10 provides the GWP100 values for hydrogen due to its effects on methane across different NO_X emission levels. The consistent GWP100 value of 5.5 across all NO_X scenarios indicates that the indirect warming effect of hydrogen through methane is not significantly influenced by NO_X levels.

Figure 43 shows how a 10% increase in surface hydrogen levels affect concentrations of OH, HO_2, and ozone in the troposphere, depending on the level of NO_X emissions. The significant reduction in OH and increase in HO_2 and ozone in high-NO_X scenarios is particularly important for understanding the indirect climate impacts of hydrogen. These effects are less pronounced in low-NO_X environments, though the overall trends remain consistent.

Table 10: Values for the hydrogen GWP100 due to changes in methane in the hydrogen perturbation experiments in the HighNO, MidNO, and LowNO atmospheres (*204*)

	HighNO	**MidNO**	**LowNO**
Total GWP100 from CH_4	5.5	5.5	5.5

Figure 43: The absolute changes in tropospheric burdens of OH, HO_2, and O_3 for a 10% increase in surface H_2 compared to no H_2 perturbation (*204*)



These studies show the complex climate interactions associated with hydrogen emissions, particularly the indirect contributions to global warming. The results indicate that hydrogen amplifies methane's warming effects and contributes to increased levels of tropospheric ozone and stratospheric water vapor, intensifying the GWP associated with hydrogen (*198*, *201*, *205*).

Potential health impacts from end-use combustion of hydrogen blends

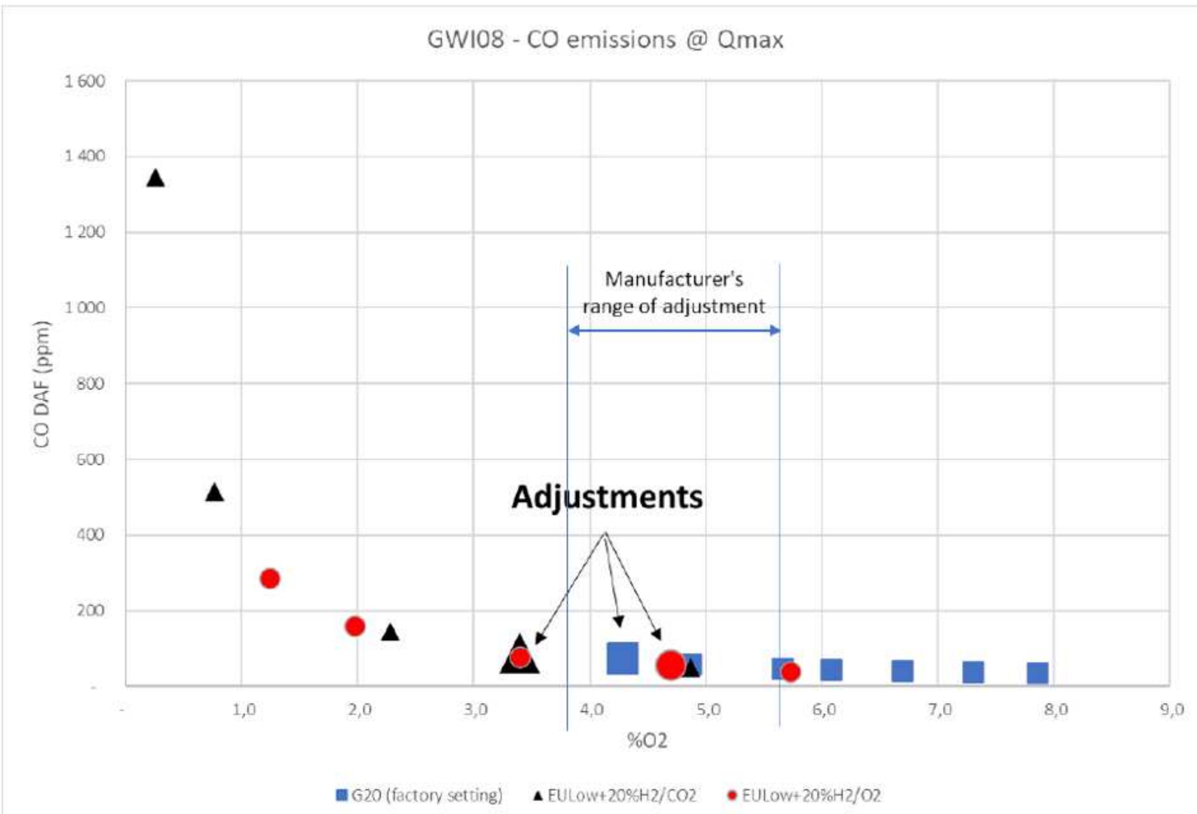
Hydrogen is non-toxic and non-poisonous. Articles on the direct health impacts of hydrogen published during the review period were not found. However, indirect impacts of hydrogen on human health have been acknowledged in the literature, especially through combustion emissions. This review includes literature on combustion emissions of blended hydrogen and natural gas mixtures published during the review period. The majority of findings summarized in Chapter 4 are related to carbon monoxide, carbon dioxide, and NO_X emissions associated with combustion properties and related flue gas properties. Additional findings associated with combustion emissions are discussed in this section.

Chapter 4 of this review presented a number of studies evaluating end-use combustion and resulting emissions. Additional studies evaluating the potential emissions impacts are discussed here. Olaniyi *et al.* evaluated the exergetic, emissions, and economic effects of hydrogen-natural gas blends in power plants (*206*). Their modeling analysis of power plants in five different countries showed that hydrogen blending reduced carbon emissions and fuel costs but led to increased NO_X emissions, due to higher adiabatic combustion temperatures associated with hydrogen blends.

Wright *et al.* conducted a meta-analysis examining the effects of blending up to 20% hydrogen into the natural gas systems of the United Kingdom, specifically focusing on NO_X emissions (*207*). Their analysis revealed that hydrogen addition could cause significant changes in NO_X levels, with a 5% hydrogen blend potentially resulting in a mean NO_X emissions increase of 8%. The study emphasized that NO_X emissions are highly sensitive to the combustion environment - non-premixed flames, due to localized high flame temperatures, exhibited larger increases in NO_X emissions, whereas pre-mixed systems demonstrated more stable and often lower emission changes.

The majority of end-use hydrogen blending projects have identified increased NO_X emissions and reduced carbon dioxide and carbon monoxide emissions. The THyGA project team explored 20% hydrogen blended with high and low heating value European natural gas in appliances (*178*). The authors reported that certain appliances, when calibrated with a low Wobbe Index gas blended with 20% hydrogen and subsequently operated with a high Wobbe Index gas devoid of hydrogen, can generate significant carbon monoxide emissions. The THyGA experimental results on adjustable boilers show increased carbon monoxide emissions in some cases. Figure 44 provides % carbon monoxide vs. % oxygen for both high and low EU gas operation using a 20% hydrogen mixture. The study also clarified that natural draft[23] is minimally impacted by a blend of up to 20% hydrogen. As a consequence, no natural draught problems are expected in the range of 0% to 40% hydrogen (*178*).

Figure 44: CO emissions as a function of the % O_2 in flue gas (*178*)



A number of articles and reports reviewed and presented in prior chapters have human health and safety as an indirect and secondary factor associated with the respective analysis. For instance, events such as leaks, permeation, and pipe and component failures can subsequently impact human health as severity, gas volumes, and hydrogen concentrations increase.

[23] Refers to passive airflow in and out of a combustion system.

CHAPTER 6: Hydrogen leak detection, monitoring, and control

The review provided in Chapter 2 summarized findings from experimental and numerical studies evaluating the effect of hydrogen blending on leak flow rates in comparison to natural gas or pure methane. The majority of these studies have demonstrated that the addition of hydrogen to natural gas or methane results in elevated leak flow rates in existing leaks, due to hydrogen's lower density and viscosity relative to methane. Direct comparisons of leaks rates of pure hydrogen and pure methane have demonstrated that hydrogen gas tends to leak at higher volumetric rates compared to methane, that are consistent with theoretical models of laminar and turbulent gas flow regimes, which state that hydrogen gas leak rate is 1.2 and 2.8 times higher than methane, respectively.

A number of numerical studies reviewed in Chapter 2, employing primarily computational fluid dynamics, have investigated the dispersion of hydrogen blended natural gas and associated risks resulting from gas leaks. The studies have revealed that under some conditions hydrogen blending in natural gas could result in larger flammable plumes due to hydrogen's higher diffusivity and buoyancy and larger volumetric leak rates. In addition, leaks of natural gas in air tend to result in accumulation of flammable gas cloud near the ground, while addition of hydrogen can result in flammable gas cloud moving upwards, depending greatly on the hydrogen concentration blended in natural gas. Furthermore, greater flame velocity and higher flammability of hydrogen result in increased fire risks associated with hydrogen blended natural gas leaks.

The safety risks associated with leaks and gas release of hydrogen blended natural gas and the environmental impacts associated with global warming potential of both hydrogen and methane gases discussed in Chapter 5, stress the importance of effective leak detection and leak mitigation strategies. This chapter discusses different leak detection methods and technologies for hydrogen and hydrogen gas blends. In addition, applicable gas leak mitigation strategies are discussed.

Gas leak detection techniques

For hydrogen blended natural gas, existing leak detection technologies can potentially detect leakage of the blended gas, although not the composition of the gas mixture. This section focuses on literature related to hydrogen leak detection technologies. Recent advancements in hydrogen sensor technology have focused on detecting hydrogen concentrations within the range of 0.1 to 10% in air (*106*). This is motivated by the development of safety detectors for early leak detection and prevention of gas accumulation above the lower flammability limit of 4% for hydrogen in confined areas. In comparison, the lower flammability limit of natural gas in air is 5%, while 20% hydrogen blended natural gas has a slightly reduced lower flammability limit in air of 4.75%. Given the environmental concerns outlined in Chapter 5 and the potential economic losses associated with leaks of hydrogen blended natural gas from the infrastructure, prevention and also detection and elimination of gas leaks is critical.

Sensor-based detection of hydrogen

There are four primary types of sensors used for detecting hydrogen: semiconductor metal oxide, electrochemical, catalytic bead, and thermal conductivity sensors, as shown in Table 11 (*208*). Semiconductor metal oxide sensors are commonly used in industry because they are cost-effective, though they have lower accuracy and are affected by humidity and temperature. Electrochemical sensors provide good selectivity for hydrogen and relatively high accuracy, though they have limited temperature ranges and slower detection times. Catalytic sensors cover a broad hydrogen detection range in terms of concentration and temperature, but they are costly and less selective for hydrogen specifically. Thermal conductivity sensors offer the widest measurement range and the highest accuracy of the four types but can have cross-sensitivity with helium. Considering the need for economical and flexible solutions in industrial settings, semiconductor-based hydrogen leak detection methods may be more practical. The main features of those four types of gas detectors are summarized in Table 11.

Table 11: Common types of sensors used in hydrogen gas detection (*208*)

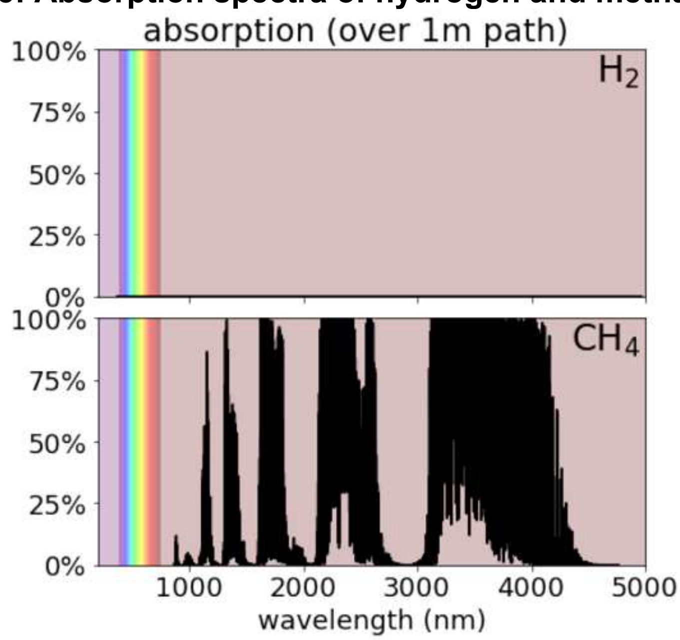
Sensor Type	Accuracy	Measuring Range	Response Time (t_{90})	Cost	Features
Semiconductor Metal Oxide	±10–30%	0–1000 ppm	<20/s	\$100 - \$500	- Low cost - Dependence on humidity and temperature
Electrochemical	< ± 4%	0–20,000 ppm	<90/s	\$300 - \$1200	- Good selectivity to hydrogen - Narrow temperature range
Catalytic Bead	< ± 5%	0–100% H_2	<30/s	\$500 - \$4000	- Wide temperature range - No hydrogen selectivity

Sensor Type	Accuracy	Measuring Range	Response Time (t_{90})	Cost	Features
Thermal Conductivity	±0.2%	0–100% H_2	<10/s	<$25,000	- High accuracy - Cross sensitive to He

Because of hydrogen's high diffusivity in air, sensor placement in relation to leak origin is crucial for accurately detecting leaks. Moreover, leak detectors normally react to concentration of hydrogen in the sampled air, which does not provide significant information about leak flow rate. These characteristics of gas sensors discussed thus far make them more suitable for enclosed areas. Additional research is required to understand how these sensors would perform when detecting mixtures of hydrogen and natural gas (*208*).

Typical methods based on optical detection, used for methane detection, such as aerial imaging relying on infrared absorption features of methane, are not applicable to hydrogen leak detection (*106*). This can be explained by the absorption spectra of hydrogen, or rather the lack of absorption bands, in the visible and infrared spectrum compared to methane as shown in Figure 45.

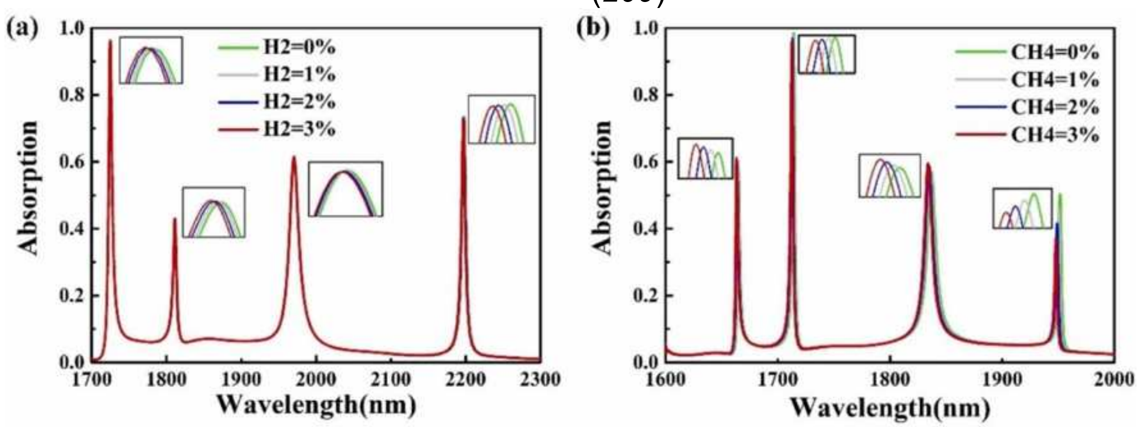
Figure 45: Absorption spectra of hydrogen and methane (*106*)



Despite this challenge, various optical methods are being explored for detecting hydrogen in air, including Shadowgraphy, Schlieren, Rayleigh, and Raman scattering (*106*). Shadowgraphy and Schlieren techniques, which are based on the bending of light rays through density variations, can detect hydrogen but are not hydrogen-specific. Rayleigh scattering, which involves elastic light scattering, has been used to measure hydrogen leaks in laboratory settings. It requires knowledge of gas flow temperature for accurate quantification, and like Shadowgraphy and Schlieren, it is not specific to hydrogen. Raman scattering, on the other hand, involves inelastic light scattering and is the only commonly used optical technique that is both specific to hydrogen and provides quantitative measurements. Raman spectroscopy has also been explored in detection of gas leaks of hydrogen blended natural gas. Despite the challenges of the Raman techniques, such as the need for high-power illumination and sensitive detectors due to its low signal strength, several research teams are focused on developing compact, Raman-based detection systems (*106*).

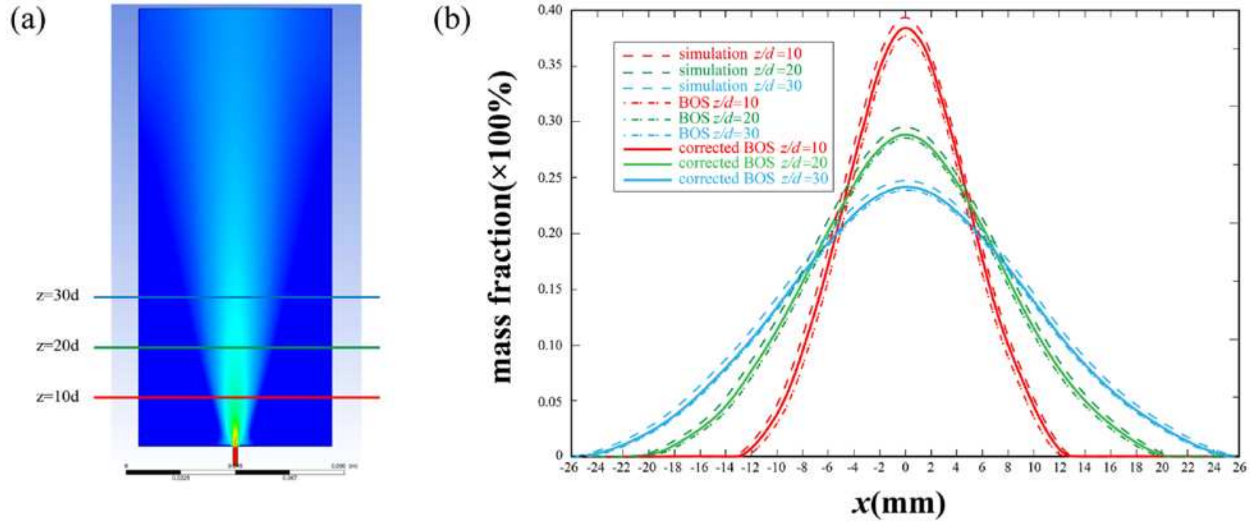
In addition to the above mentioned, some novel optical detection methods are being explored. Wang *et al.* proposed a detection technique for hydrogen and methane in inert gases, based on change in the refractive index of a gas sensitive membrane, which works in the near-infrared band with wavelength of 1700 - 2600 nm (*209*). Figure 46 (a) shows shift in absorption band with change in hydrogen concentration, while Figure 46 (b) shows absorption band change with change in methane concentration.

Figure 46: Absorption spectra of (a) 0 - 3% hydrogen, and (b) 0 - 3% methane (*209*)



Sun *et al.* demonstrated a non-contact optical detection method based on background oriented Schlieren (BOS) technique to detect hydrogen leak and quantify its concentration in air (*210*). Figure 47 (a) shows a simulated hydrogen gas jet, while Figure 47 (b) compares BOS and CFD simulated hydrogen concentration distribution curves at three different distances (10d, 20d, 30d) from the nozzle.

Figure 47: (a) Hydrogen gas jet, (b) BOS and CFD radial concentration distribution curves at three different heights (*210*)



Shaposhnik *et al.* have proposed a metal oxide sensor with selectivity for hydrogen in hydrogen-methane gas blends, based on tin dioxide with additions of palladium and platinum (*211*). The sensor operates on the principle of detecting changes in resistance with modulation of temperature.

Experimental work conducted as part of the HyDeploy project in Great Britain evaluated various industry gas leak detectors with hydrogen blended in methane at concentrations of up to 20% (*212*). The study revealed that a number of gas detectors currently used for natural gas and carbon monoxide are cross sensitive to hydrogen in the gas blends tested. In particular, electrochemical carbon monoxide detectors can trigger a false alarm due to indoor leak of hydrogen blended natural gas that is within the permissible level.

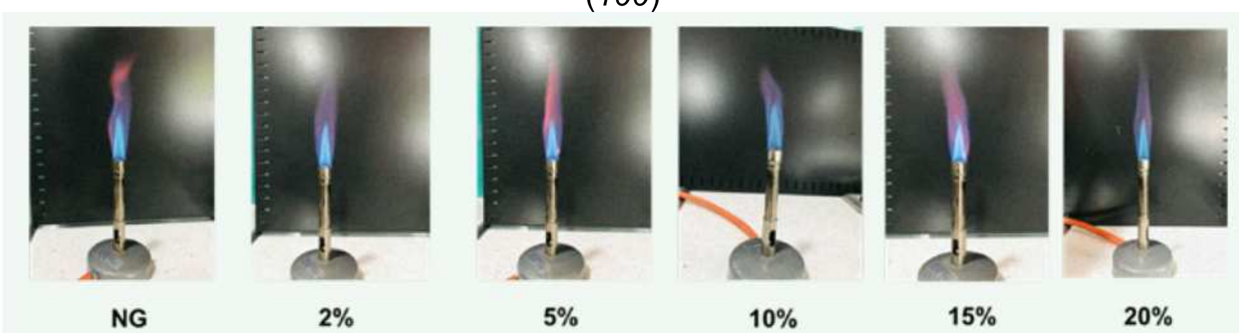
Odorization

An alternative method for detecting leaks of hydrogen blended natural gas is gas odorization, which is the addition of chemical odorants that are detectable by smell to the gas (*208*)A number of studies have evaluated the effectiveness of commonly used odorants for pure hydrogen and hydrogen-natural gas blends.

The HyDelta project in the Netherlands tested tetrahydrothiophene (THT), a commonly used natural gas odorant in Europe, in addition to the sulfur-free odorants Gasodor S-Free and 2-hexyne with hydrogen gas (*213*). The investigation revealed that all odorants remained stable in a hydrogen environment throughout a three-month test period, with no separation occurring between the odorant and hydrogen upon gas leakage. A report from a European MARCOGAZ Odorization Working Group has stated that sulfur based odorants like THT or mercaptans are unlikely to react chemically with hydrogen in gas distribution grids (*50*). Furthermore, project Hy4Heat in Great Britain concluded that the odorant currently used in the natural gas distribution network, Odorant NB (New Blend), is suitable with 100% hydrogen use (*214*). Finally, the pilot project Hydrogen Park South Australia (HyP SA), which is providing 5% hydrogen blended natural gas to approximately 700 residential and commercial customers, has found that that odorant levels were not impacted by 5% hydrogen blending (*84*).

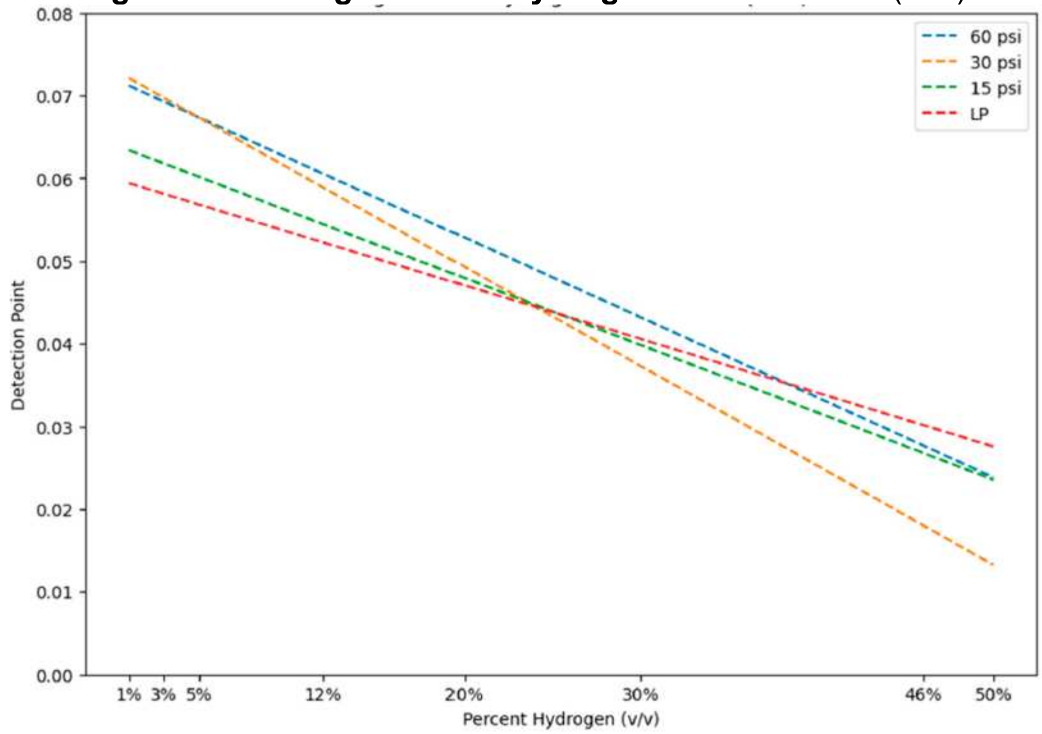
Several studies have explored the impacts of hydrogen blending impacts on flame color and odorant suitability. Differences in the physical combustion appearance and differences in odorants associated with unburned gas require consideration for blended gas operations. Combustion of 100% hydrogen is known to be visually indiscernible in daylight conditions. Figure 48 shows the visual flame differences of hydrogen blended gases ranging from 100% natural gas to 80% natural gas blended with 20% hydrogen.

Figure 48: Flame characteristics of burning blends of hydrogen and natural gas (*100*)



Kileti *et al.* evaluated the readily detectable level (RDL) representing the concentration in air at which one recognizes an odor as a natural gas odor (*215*). As the hydrogen blending percentage increased, the measured RDL decreased on average (Figure 49). The authors determined that the odorant in the blended gas, Scentinel–E, maintained its chemical integrity, indicating that no chemical reaction occurred in the pipeline. The odorant did not fade or undergo odorant masking in hydrogen mixes of up to 50% by volume. The authors determined that, under the conditions evaluated, the odorant is an effective leak detection tool for the hydrogen blends that can be effective for both service workers and customers.

Figure 49: Average RDL vs. Hydrogen Concentration (*215*)

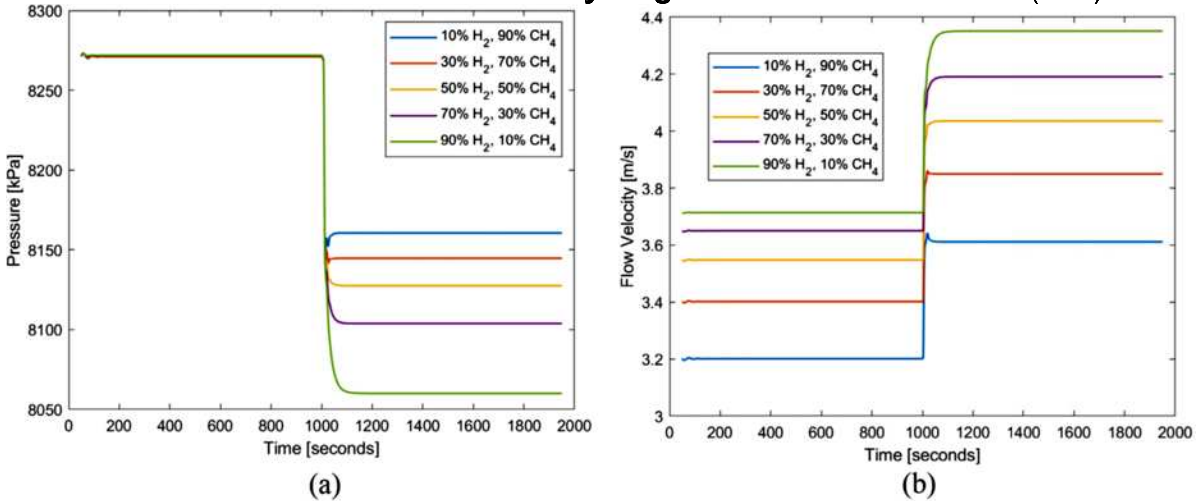


The Hy4Heat project findings suggest odorant effectiveness to be unchanged by hydrogen blending and presumes consumer behavior to remain unchanged from natural gas to hydrogen gas, including their response to a suspected leak, because the same odorant will be used for hydrogen gas (*91*). This can ensure that the familiar smell people are used to responding to is unchanged.

Computational pipeline monitoring

Computational pipeline monitoring (CPM) uses computer systems to detect leaks by tracking changes in measured pipeline data across networks, such as a supervisory control and data acquisition system, which gathers sensor data from pipelines and uses the data to identify leaks (*208*). Figure 50 shows the simulated transient response of a gas pipeline pressure and gas flow velocity to a gas leak, at different concentrations of hydrogen blended in methane. The leak event occurs at 1000 sec, from a leak with diameter that is 10% of the pipe's internal diameter. Figure 50 (a) shows the change in upstream pressure over time, while Figure 50 (b) shows change in pipeline gas flow velocity, for hydrogen blended in methane at concentrations from 10% to 90%. This simulation demonstrates that while hydrogen-natural gas blend may have different density and viscosity depending on the hydrogen blending concentration, the computational pipeline monitoring technique is equally effective for detecting leaks of hydrogen blended natural gas as long as the composition of the gas blend is known.

Figure 50: Gas leak effect on (a) pipeline pressure, (b) pipeline gas flow velocity, for different concentrations of hydrogen blended in methane (*208*)



Pipeline operations and repair activities

The majority of studies reviewed have operations with blends of up to 20% hydrogen and associated impacts on materials, system functionality, end-uses, and potential leak considerations. Few studies have determined that significant changes are required for procedural maintenance and operations with hydrogen blends below 20%. The HyDelta 2 project identified the need for considerations associated with portions of the transmission infrastructure targeted at 100% hydrogen (*108*). HyDelta 2 addressed safety concerns relative to 100% hydrogen in the high pressure system and related isolation techniques. Table 12 lists potential isolation methods recommended by the HyDelta 2 project depending upon location with respective advantages and disadvantages.

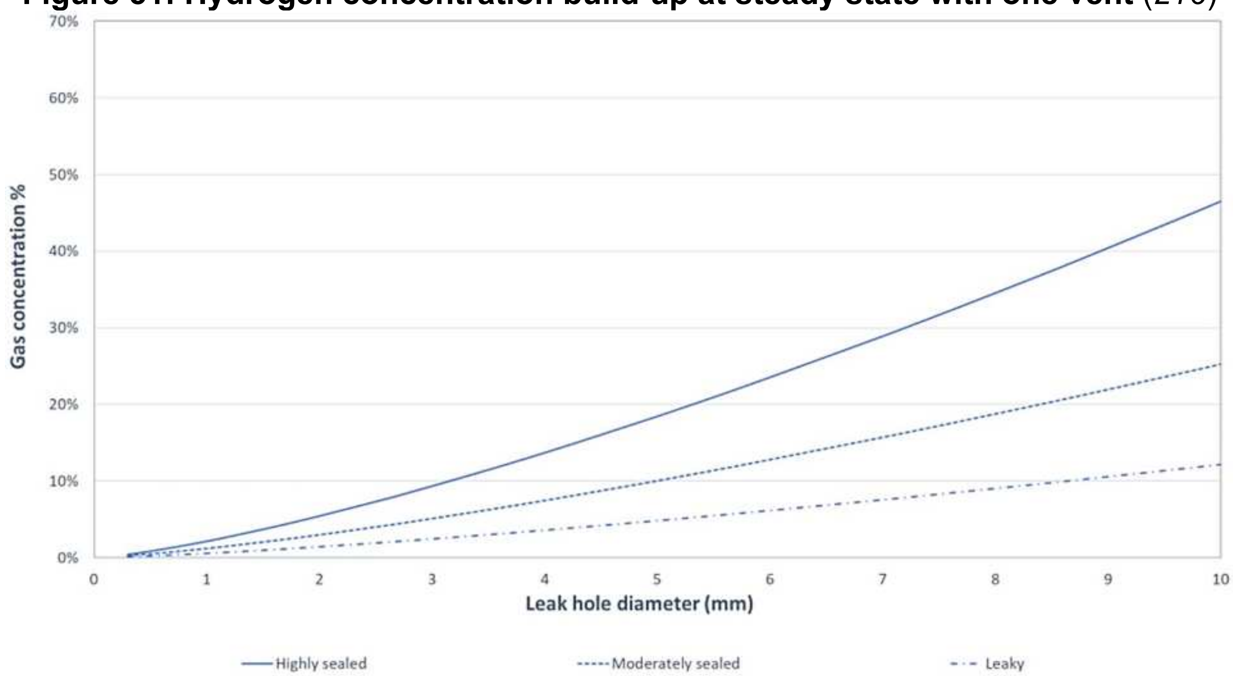
Table 12: Hydrogen high pressure pipeline isolation methods with advantages and disadvantages (*108*)

Isolated section	Preferred evacuation technique	Advantages	Disadvantages
Between valve schemes with pigging facilities (50-100 km distance)	Purging with a separation pig	• Minimizes the mixing of hydrogen and nitrogen • No stratification problems and smaller diffusion front • Evacuation method is similar to natural gas	• Large loss of gas volume • possible disruption of suppliers and industrial consumers • Higher flowrates along the PIG with respect to natural gas pigging
Between valve schemes without pigging facilities (10-50 km distance)	Purging	• No disruption of suppliers and industrial consumers • Evacuation method is similar to natural gas	• Possible large loss of gas volume • Stratification issues will arise more often with respect to natural gas
Installing temporary seal with stopple	Purging	• Limited loss of gas volume • Possibility to install temporary bypass	• Current evacuation methods used for natural gas will not suffice • More research needed on stopple trains and hydraulic stopples
Valve schemes (installation, complex piping systems)	Dilution-based purge	• Can be applied in many cases • More effective hydrogen dilution with respect to natural gas dilution.	• Multiple cycles of nitrogen purging needed before successful purge.

Scenario evaluation of confined domestic hydrogen gas leaks

The Hy4Heat project evaluated potential scenarios of domestic gas leaks comparing 100% natural gas vs. 100% hydrogen. The evaluation explored gas concentration buildup, potential ignition sources, and potential damage (*93*, *107*, *216*). Figure 51 shows hydrogen concentration buildup relative to leak size at steady state. The scenarios evaluated in Hy4Heat explored gaseous buildup and risk associated with leaks in confined space. The Hy4Heat overall Quantitative Risk Assessment (QRA) indicates that usage of 100% hydrogen can be made as safe as natural gas when used for heating and cooking in detached, semi-detached, and terraced houses of standard construction (*91*).

Figure 51: Hydrogen concentration build-up at steady state with one vent (*216*)



Makaryan *et al.* conducted a literature review on the use of hydrogen methane blends and highlighted safety and compatibility challenges within existing infrastructure, emphasizing the need for secure storage and distribution systems for large-scale hydrogen use. The authors suggest that the most promising approach in the near future is the use of methane–hydrogen blends with up to 20% hydrogen concentration for energy production and in the domestic sector (*217*).

Gas leak mitigation

The Hy4Heat and H21 demonstration projects in Great Britain have experimentally investigated the leak rates of hydrogen and methane from common components used in the natural gas distribution system (*92*, *94*). Their findings, which are discussed in detail in Chapter 2, revealed that components which leaked with hydrogen gas also leaked with methane gas, and repairs conducted on leaky components employing standard methods for natural gas systems, were equally effective in eliminating the leaks for methane and hydrogen gases (*94*). This suggests that standard repair methods of leaks in natural gas systems may be effective for blends of hydrogen in natural gas, given that the materials used are compatible with hydrogen.

Leaks due to permeation of hydrogen gas through polymers, specifically thermoplastics used in natural gas distribution pipelines, are discussed at length in Chapter 3. Since hydrogen's permeation rate could be several times higher than methane's in some common polymers, it could lead to preferential leak of hydrogen over methane through polymer pipelines. This type of leak is difficult to address without replacing these polymeric materials with materials that have lower rates of permeation of hydrogen or by using other effective strategies. However, as discussed in Chapter 3, estimates of hydrogen loss due to permeation in MDPE, HDPE, and PA11 pipes, are fairly low (0.066%, 0.019%, and 0.011%, respectively) (*55*).

CHAPTER 7: Impacts on natural gas storage fields

Storing either pure hydrogen or natural gas hydrogen blends in depleted gas and oil reservoirs involves important considerations due to hydrogen's small molecular size, high diffusivity, and buoyancy, which may influence containment and recovery efficiency. By studying and understanding these characteristics, researchers can better address key aspects and optimize strategies for safe and efficient hydrogen storage in such geological formations. Due to hydrogen's higher mobility and lower density than methane, it tends to migrate to the upper parts of the reservoir, making containment in geological formations such as depleted gas fields, essential for maintaining safety during storage operations. These properties necessitate adjustments in injection and withdrawal strategies to minimize leakage and improve recovery, particularly under varying pressure conditions. In addition to its mobility challenges, hydrogen's interactions within the reservoir introduce further complexities. Specifically, hydrogen's interactions with surrounding rock and brine systems increases the risk of leakage and gas migration compared to natural gas, particularly in depleted gas reservoirs and can significantly impact storage safety. Wettability, interfacial tension, and the presence of organic materials in the reservoir rock play crucial roles in determining the sealability of storage sites and the potential for hydrogen migration. These parameters help define the containment security of the storage site and the effectiveness of the caprock seal, which is essential for long-term hydrogen storage (*218*). Depleted gas and oil reservoirs are considered a cost-effective storage option due to their existing infrastructure; however, they face challenges such as hydrogen losses driven by hydrodynamic, geochemical, and microbial factors. Specifically, microbial activity can significantly affect storage fields, as certain bacteria convert hydrogen into methane or hydrogen sulfide, increasing the risk of potential hydrogen sulfide contamination and changes in gas composition (*219*).

Addressing these issues requires advanced well-completion methods and materials tailored for hydrogen environments to ensure the long-term safety and viability of storage fields (*220*). Effective containment and control measures are necessary to prevent unintended releases, especially given hydrogen's propensity to leak through small gaps and permeate materials more readily than other gases (*96*, *197*). Coatings and liners used in pipelines and wells are crucial for maintaining the integrity of hydrogen storage systems. Given hydrogen's potential to cause embrittlement and corrosion, ongoing improvements in coating and liner technology are necessary to ensure the long-term durability and safety of storage infrastructure.

Operations and modifications to storage fields

Huang *et al*., developed a numerical model to assess the feasibility and operational challenges of underground hydrogen storage (UHS) in depleted gas reservoirs (DGR), evaluating the performance of hydrogen blended with methane, nitrogen, and CO_2 (*221*). The study evaluated the performance of cushion gases like nitrogen and carbon dioxide, finding that nitrogen was more effective for enhancing hydrogen recovery due to its higher gas compressibility and lower solubility in water. Nitrogen facilitated a 91% hydrogen recovery rate, outperforming carbon dioxide, which achieved an 81% recovery. This efficiency stems from nitrogen's ability to maintain pressure and support gas phase expansion during withdrawal.

A significant finding was the role of gravity segregation in the reservoir, where hydrogen, being less dense, migrates to the upper sections, displacing heavier gases like methane. Effective management of injection and withdrawal cycles is necessary to prevent methane entrapment, which could otherwise reduce hydrogen recovery efficiency. The study underscores the need for strategic cycle management and cushion gas pre-injection to optimize UHS operations. Figure 52 presents results from the study, illustrating gas saturation, methane mole fraction, and hydrogen mole fraction profiles at various stages, showing how these distributions evolve over time due to gravity segregation and injection strategies.

Figure 52: Gas saturation (a), methane mole fraction (b), and hydrogen mole fraction (c) distributions on days 10, 150, 210, and 360, respectively (*221*)

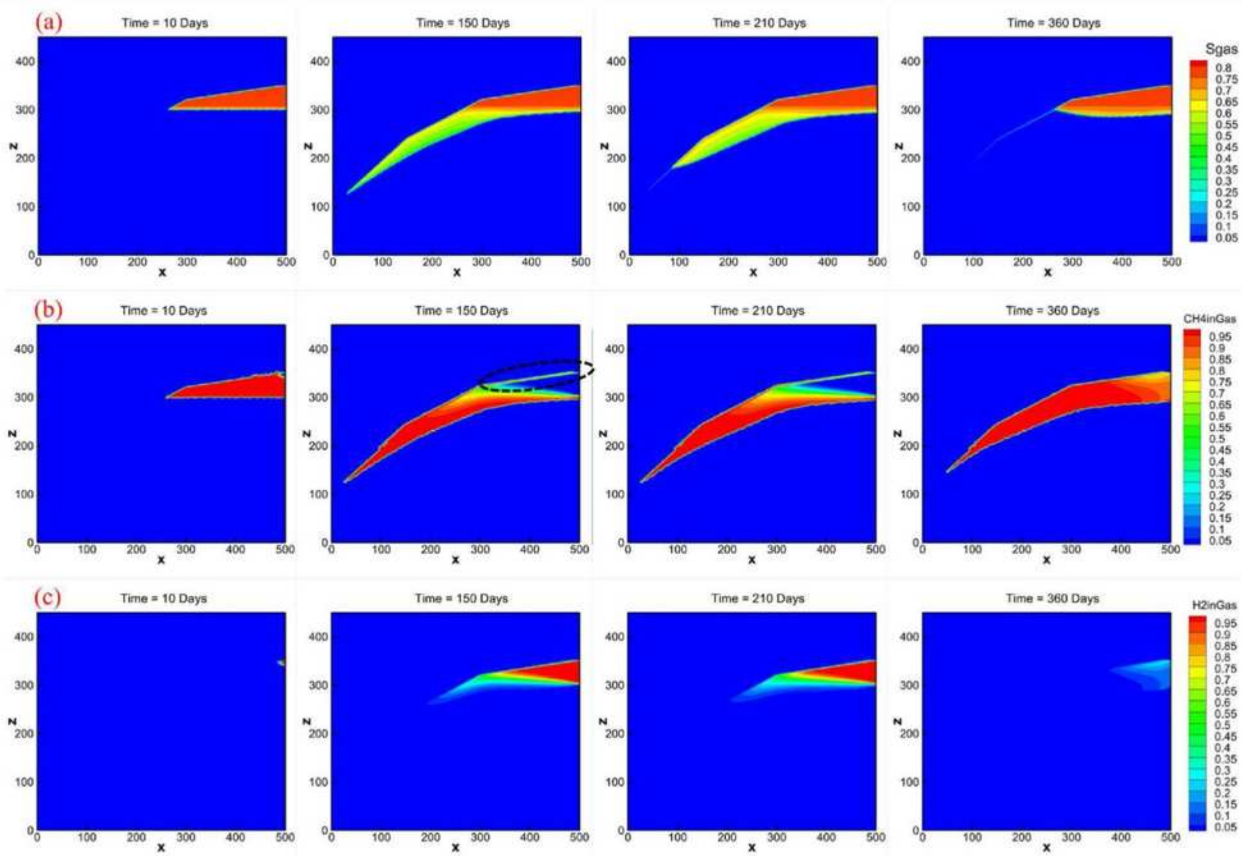
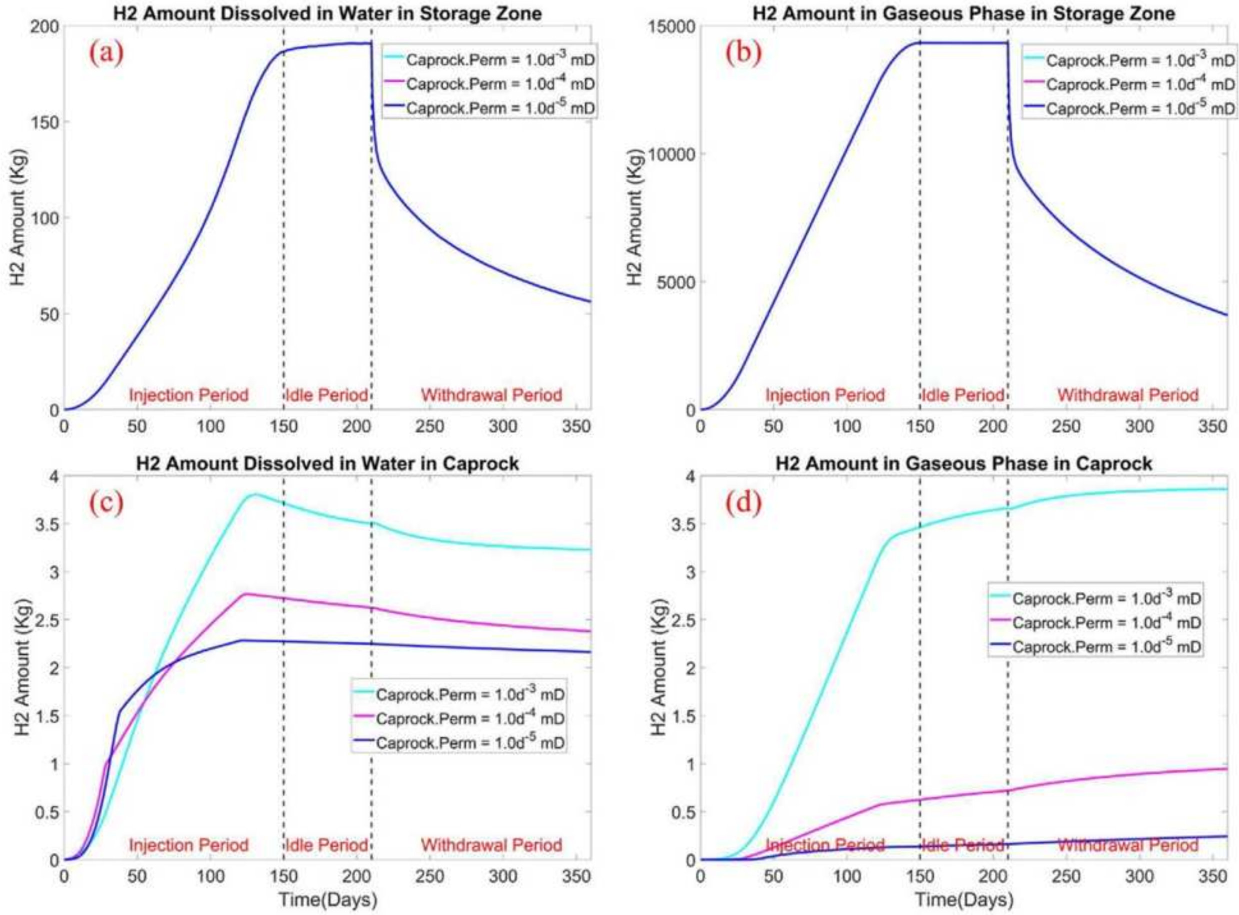


Figure 53 examines the influence of caprock permeability on hydrogen leakage in underground hydrogen storage systems. The simulation results reveal that variations in caprock permeability significantly affect the distribution of hydrogen in both the storage zone and caprock. For instance, hydrogen dissolution in the aqueous phase within the storage zone is depicted in Figure 53 (a), while the gaseous hydrogen phase is shown in Figure 53 (b). Figure 53 (c) and (d) further illustrate hydrogen behavior in the caprock, where higher permeability facilitates increased hydrogen movement into both gaseous and aqueous phases. However, even at a permeability level of 10^{-3} mD, only about 0.05% of the injected hydrogen is lost to the caprock, underscoring the containment reliability of depleted gas reservoirs for hydrogen storage.

Figure 53: The variation of hydrogen amount in the storage zone and cap-rock (*221*)



Maintaining well integrity is crucial, especially in high-pressure storage or when repurposing older fields previously used for natural gas, where legacy materials may not be sufficiently resilient (*220*). A recent review by the National Energy Technology Laboratory (NETL) covered potential hydrogen hazards related to gas turbines, solid oxide fuel cells, and associated systems and materials. The authors highlighted the risks of hydrogen embrittlement and corrosion, recommending infrastructure upgrades, particularly in well completion materials, to enhance durability and extend the operational lifespan of storage fields (*161*).

Camargo *et al.* explored the dynamics of a natural gas fields when used for hydrogen storage, by developing a viscosity model for hydrogen-containing gas mixtures (*222*). The study emphasized the necessity of frequent adjustments in operational cycles, particularly injection and withdrawal cycles, to optimize hydrogen recovery ratios and counteract inefficiencies due to hydrogen's buoyancy and rapid migration One recommended approach is to use natural gas as a cushion gas, which supports reservoir pressure and prevents native brine intrusion. However, during withdrawal, hydrogen's tendency to migrate above the cushion gas can reduce recovery efficiency, necessitating careful cycle adjustments.

Figure 54 illustrates the variations in hydrogen mass fraction in the produced gas for different injection blends: Figure 54 (a) 15% hydrogen in methane, Figure 54 (b) 50% hydrogen in methane, and Figure 54 (c) pure hydrogen. This figure highlights the role of cushion gases and the impact of different gas compositions on hydrogen recovery and segregation behavior within the reservoir.

Figure 54: H_2 mass fraction in the produced gas when injecting (a) 0.15 H_2/0.85 CH_4 (mass fraction) blend, (b) 0.5 H_2/0.5 CH_4 (mass fraction) blend, and (c) pure H_2 (*222*)

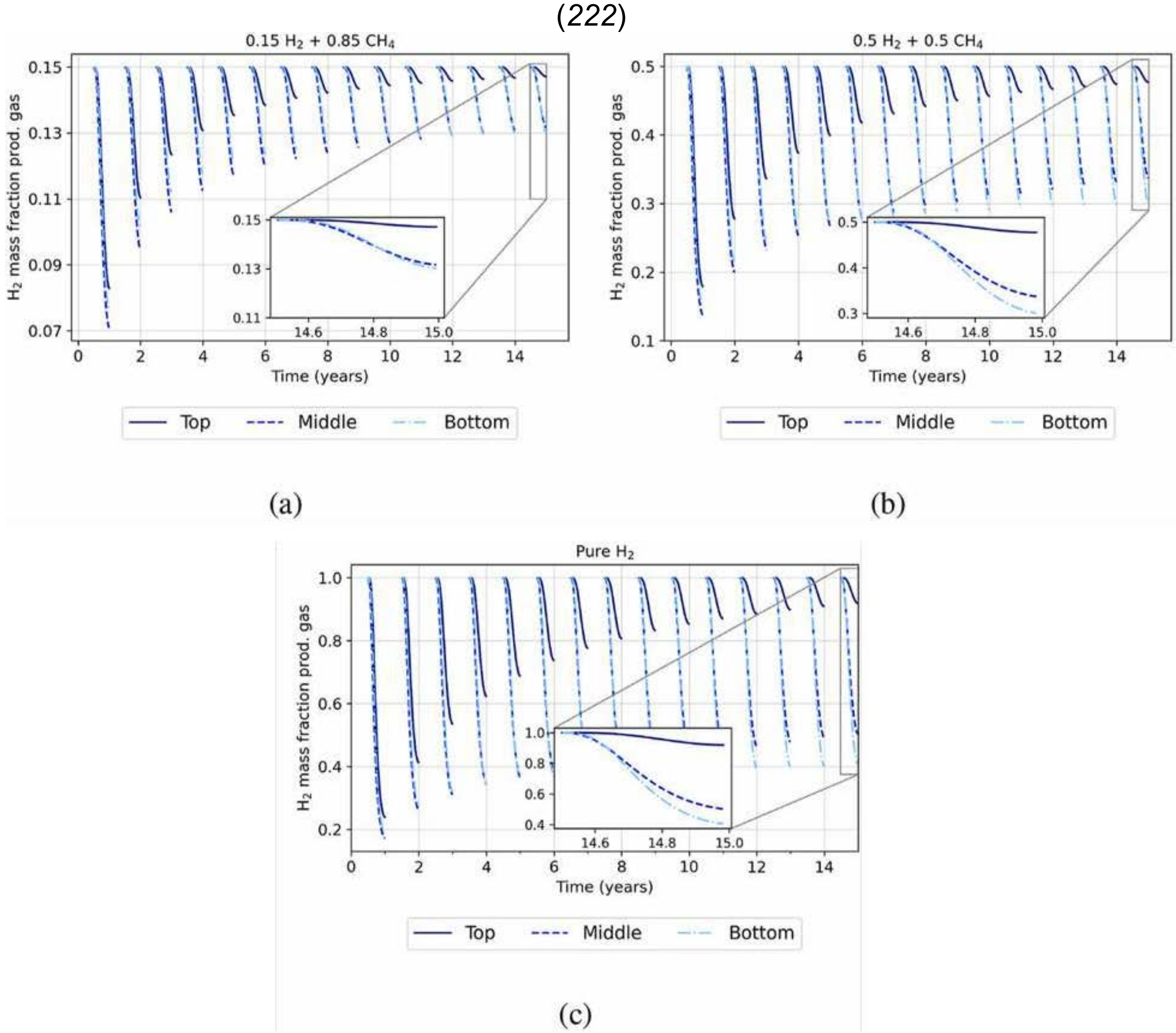
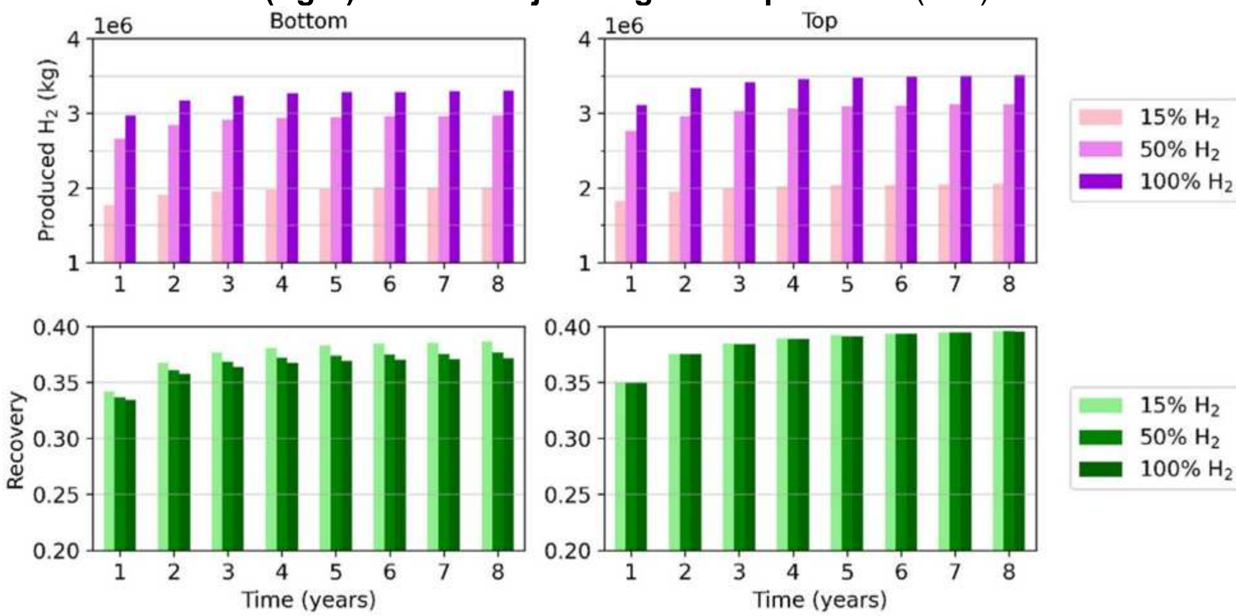


Figure 55 shows the simulated mass of produced hydrogen and recovery ratio over the first 8 years, with comparisons between perforating the bottom versus the top of the reservoir for three gas compositions: 15% H_2, 50% H_2, and 100% H_2. This figure illustrates how strategic well perforations and operational adjustments impact hydrogen recovery efficiency.

Figure 55: Mass of produced hydrogen (top) and recovery ratio (bottom) during the first 8 years, when perforating the bottom (left) or the top of the reservoir (right) for three injected gas compositions (*222*)



To further optimize storage operations, reservoir simulations have highlighted the importance of geomechanical properties, such as caprock integrity and wellbore sealing, in maintaining long-term storage efficiency and mitigating leakage risks. Continuous monitoring of caprock integrity is essential to detect early signs of hydrogen leakage, even in cases of increased permeability (*218*, *223*). Technologies such as fiber-optic-sensors are recommended for real-time monitoring of potential micro-cracks in wellbores or caprock, providing early detection of leakage events (*197*). This proactive approach to monitoring ensures that structural integrity is maintained, even in complex reservoir dynamics.

Additional strategies proposed include optimizing well depths, employing varied gas injection methods, and implementing buffer gases to enhance hydrogen recovery efficiency. These operational modifications are designed to mitigate hydrogen migration issues, supporting a more stable and efficient recovery process (*197*).

In summary, operational adjustments, strategic use of cushion gases, and robust monitoring technologies are pivotal in maintaining storage field integrity and optimizing hydrogen recovery. As shown in Figure 54 and Figure 55, a combination of nitrogen-based cushion gases, adaptive injection cycles, and tailored well perforations can improve hydrogen storage efficiency by addressing the challenges posed by hydrogen's unique physical characteristics.

Delshad *et al.* utilized modeling approach to analyze the unique challenges of hydrogen storage by comparing it to natural gas and carbon dioxide storage, with a focus on gas containment, working capacity, and well integrity, especially in depleted oil reservoirs (*224*). Due to hydrogen's lower density and viscosity compared to natural gas, it tends to spread more laterally and vertically within the reservoir, and poses containment challenges, particularly in porous formations where hydrogen can migrate further than natural gas.

Figure 56 illustrates the comparative gas volumes of hydrogen and natural gas, in billion standard cubic feet (BSCF), at a Colorado site, showing that hydrogen reaches peak pressures faster, which in turn reduces the working gas capacity of storage sites. This behavior underscores the need for operational adjustments to manage pressure buildup effectively and maintain storage integrity during hydrogen storage cycles.

Figure 56: Gas volumes for H_2 and NG - Colorado site (*224*)

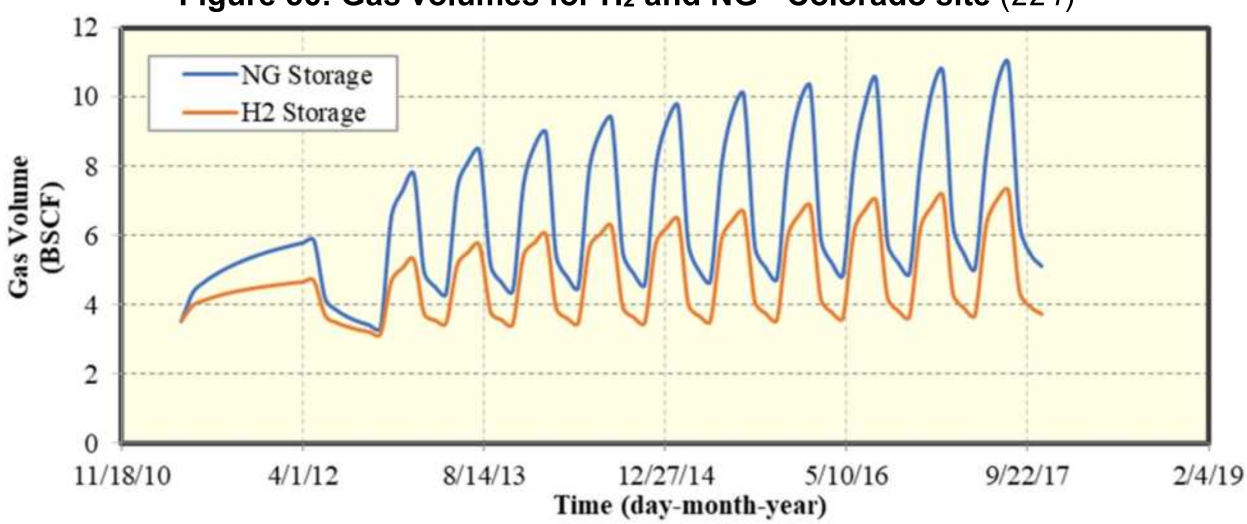
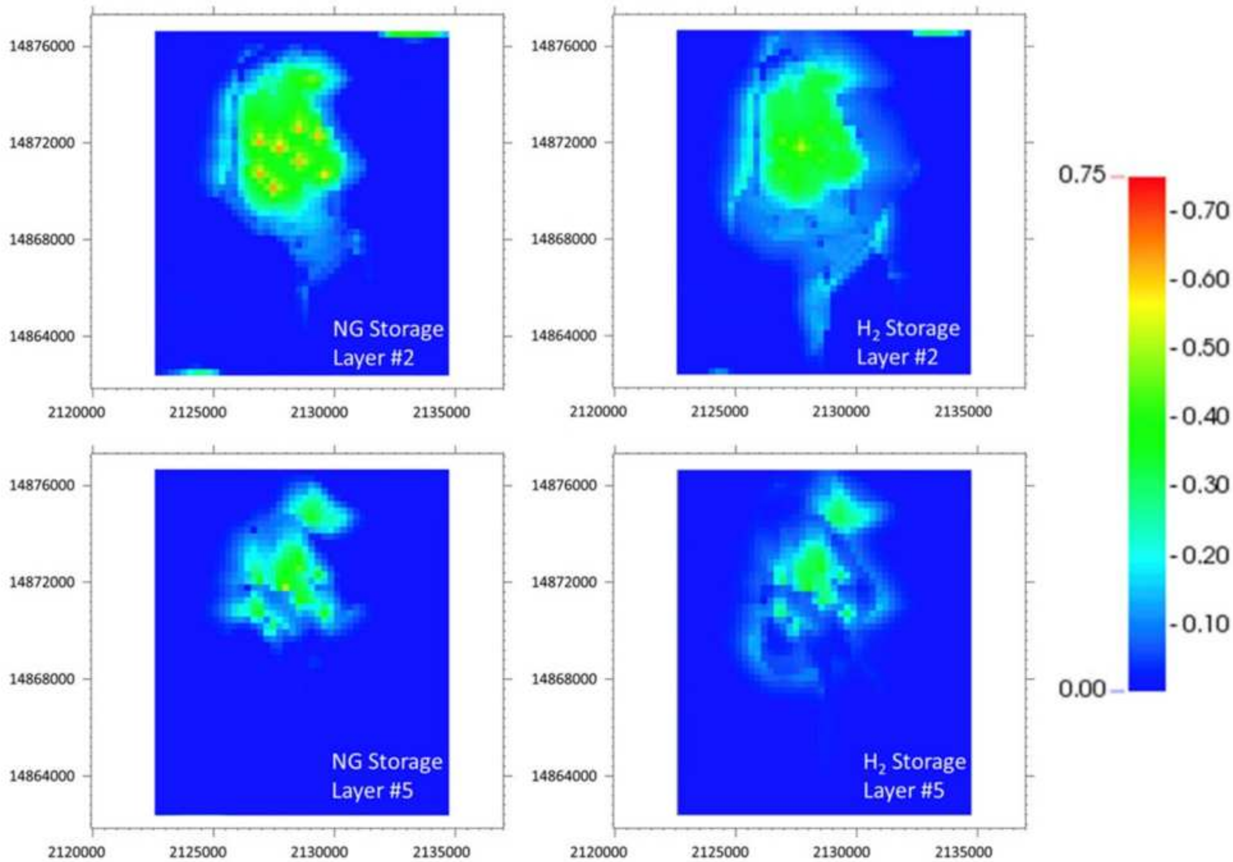


Figure 57 provides visual evidence of the difference in saturation growth between hydrogen and natural gas within the reservoir at the Colorado site, highlighting layers 2 and 5. The images reveal hydrogen's more extensive lateral and vertical spread, confirming its increased mobility compared to natural gas. This visualization underscores the importance of strategic well placement and tailored injection strategies to manage hydrogen's behavior effectively and minimize migration risks.

Figure 57: H_2 (right images) and NG (left images) saturation growth in the middle of storage time in layers 2 (top images) and 5 (bottom images) - Colorado site (*224*)



Hydrogen's interactions with reservoir rock and fluids pose storage challenges, particularly in depleted oil and gas reservoirs. Research indicates that over time, chemical reactivity between hydrogen and reservoir materials can impact both containment and recovery efficiency. Geochemical reactions, such as mineral dissolution and precipitation, may alter reservoir permeability, potentially affecting hydrogen containment and increasing the risk of leakage. This interaction is especially relevant in formations with carbonate minerals, as hydrogen can lead to changes in pH levels, promoting the dissolution of certain minerals and impacting caprock integrity. Consequently, continuous monitoring of reservoir conditions is crucial to maintaining storage efficiency and safety in underground hydrogen storage projects (*219*).

A review by Thiyagarajan *et al.* highlighted key operational challenges in hydrogen storage, particularly the risks posed by hydrogen's high mobility and diffusivity, which can lead to leakage through faults or wellbore imperfections (*225*). Additionally, microbial activity may degrade stored hydrogen, converting it into methane or corrosive hydrogen sulfide, further complicating recovery and posing risks to well integrity. These findings reinforce the need for enhanced monitoring and robust material selection to maintain safe and efficient storage operations.

To address the technical challenges in hydrogen storage, Ugarte *et al.* highlight the need for robust monitoring techniques and effective mitigation strategies to minimize hydrogen loss during storage operations (*220*). Kumar *et al.* underscore the brittleness induced in steel components exposed to hydrogen, a phenomenon that stresses the need for improved well designs and advanced sealing technologies to maintain well integrity and minimize leakage over long storage durations (*226*).

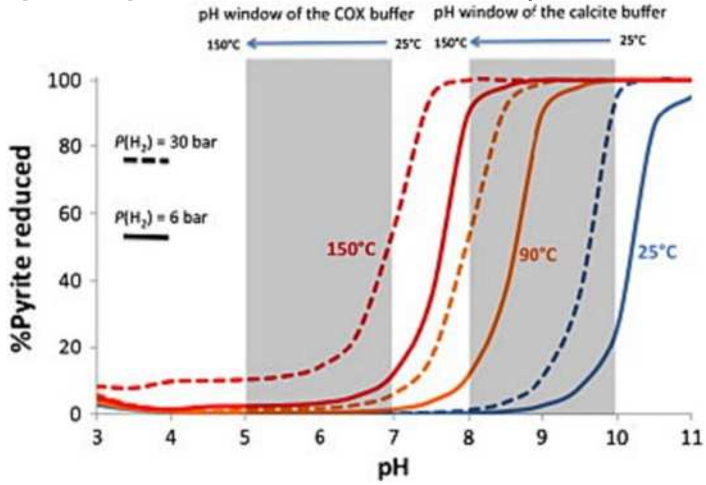
Additionally, geochemical reactions between hydrogen and subsurface rock formations can impact long-term storage performance. Muhammed *et al.* highlight that over extended periods, these reactions, including mineral dissolution and precipitation, may alter reservoir properties such as permeability and porosity, which are essential for maintaining containment and effective hydrogen recovery. This process emphasizes the need for further research to understand the complex interactions between hydrogen and reservoir materials, as slow reactions could gradually compromise storage integrity. Continuous monitoring and further investigation into these geochemical processes are recommended to ensure the long-term safety and efficiency of underground hydrogen storage (*219*).

Sealability and well integrity

Zeng *et al.* examined the complex interplay of geochemical, mechanical, and microbial factors that impact the integrity of caprock and wellbore materials in underground hydrogen storage systems within depleted gas reservoirs (*227*). Additionally, microbial activities, particularly from sulfate-reducing bacteria, can induce the production of corrosive byproducts like hydrogen sulfide, further degrading wellbore materials and impacting overall storage integrity.

Figure 58 illustrates the dissolution of pyrite as a function of pH across varying temperatures and hydrogen partial pressures, underlining the geochemical challenges associated with maintaining storage containment in these geological formations.

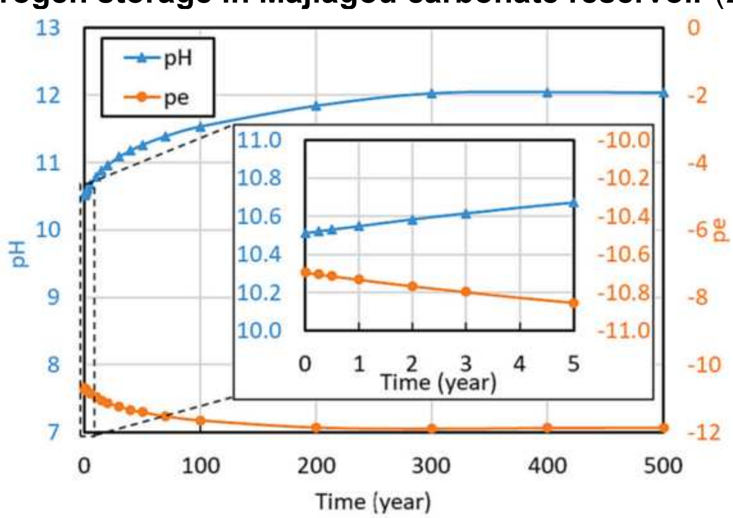
Figure 58: Dissolved pyrite as a function of pH, from 25 to 150 °C (77 to 302 °F), at hydrogen partial pressures of 6 and 30 bar (87 and 435 psi) (*227*)



Zeng *et al.* explored the stability of hydrogen storage in carbonate reservoirs, emphasizing risks related to pH variations and their impact on reservoir integrity (*227*). Their study identified gaps in existing research, particularly regarding long-term data on how cyclic hydrogen injection and withdrawal affect caprock and wellbore stability. The research highlights the need for further experimental and simulation studies due to the high reactivity of hydrogen with carbonate minerals, especially under varying pressures and temperatures. These interactions could influence storage integrity through mineral dissolution and secondary geochemical changes.

Figure 59 illustrates potential shifts in pH and pE over a theoretical 500-year scenario, highlighting possible long-term trends, though practical storage projects typically consider much shorter timescales.

Figure 59: The variation of pH and pE over 500 years during underground hydrogen storage in Majiagou carbonate reservoir (*227*)



Maintaining wellbore integrity is a critical to underground hydrogen storage, especially in repurposed gas reservoirs where materials may be susceptible to hydrogen-induced degradation. Morgan *et al.* discussed the challenges posed by hydrogen embrittlement (*96*).

A study by Ugarte *et al.* provided a comprehensive analysis of well integrity challenges associated with UHS (*220*). Ugarte *et al.* examined mechanisms that compromised well integrity in UHS, drawing comparisons with other storage systems, such as underground gas storage and carbon capture and storage (CCS). The study identified key mechanisms of degradation, including microbial corrosion, hydrogen embrittlement, cement degradation, elastomer failure, and caprock sealing failure.

Microbial-induced corrosion (MIC) was highlighted as a significant risk for UHS. In hydrogen storage environments, sulfate-reducing bacteria (SRB) utilized hydrogen as an electron donor, producing hydrogen sulfide, which accelerated corrosion on metallic well components. Table 13 presents a comparison of UHS (hydrogen storage in depleted gas reservoirs), UGS (natural gas storage in depleted gas fields), and CCS (carbon dioxide storage in geological formations), emphasizing unique risks in hydrogen storage, such as hydrogen blistering and embrittlement, which were less prominent in other storage types (*220*).

Table 13: Comparison between UGS, CCS, and UHS with respect to different mechanisms affecting well integrity (*220*)

	UGS (Natural Gas)	**CCS (Carbon Capture)**	**UHS (Hydrogen)**
Corrosion	Depends on the selected geological formation, rock minerals, gas composition, pH, temperature, and salt concentration	Galvanic, pitting, and crevice corrosion. Carbonic acid from scale of iron carbonate as a corrosion product	High risk due to microbial organisms and hydrogen availability as an electron donor. Microorganisms' survival depends on pH, temperature, and salt concentration
Hydrogen blistering, HIC, and hydrogen embrittlement	Medium risk depending on the availability of hydrogen near the metal surfaces	Low due to lack of hydrogen presence	Due to abundance of hydrogen can increase the susceptibility to cracking at lower stresses, reduction of material ductility, and resistance

Cement carbonation	Reaction will depend on the amount of CO_2 found in the rock mineral and formation fluids	High risk due to abundance of CO_2 forming carbonic acid. Temperature and pH can aggravate degradation	Reaction will depend on the amount of CO_2 found in the rock mineral and formation fluids
Sulphidation	Depend on the amount of H_2S that can be found in the environment. Low pH can make pyrite become part of H_2S producing reactions	Low risk due to less probability of finding high amount of H_2S	Higher risk as H_2S is a by-product of microbial reactions caused by SRB
RGD	Methane can permeate and cause physical properties alteration	High risk as CO_2 in gas phase can cause degradation and permeate the elastomer element	Due to hydrogen physical properties, it can easily permeate the elastomer. Severity is proportional to temperature, pressure, and time
Elastomer degradation	Natural gas will not react chemically with the elastomer	High risk when elastomer material is in contact with carbonic acid	Moderate to high as H_2S by-product of SRB can cause a reduction of tensile strength, ultimate elongation, and hardness
Caprock integrity	Higher interfacial tension in a methane-water system results in high capillary pressure and less risk of leakage	If dissolution rates are greater than precipitation rates in the caprock, efficiency may increase due to porosity and permeability enhancement leading to potential leaks	Low interfacial tension in a hydrogen-water system results in low capillary pressure and high risk of diffusion

Additionally, Ugarte *et al.* emphasized the importance of designing wells specifically for hydrogen's properties, recommending the use of corrosion-resistant materials, such as high-nickel alloys, to mitigate hydrogen embrittlement. Elastomer materials and sealing techniques also required careful selection to prevent hydrogen leakage, particularly under fluctuating pressure conditions during injection and withdrawal cycles (*220*).

Continuous monitoring was deemed crucial for maintaining well integrity in UHS. Techniques such as cement bond logs (CBL), variable density logs (VDL), and corrosion logs were recommended for ongoing assessment, as summarized in Table 14. These monitoring methods allowed for early detection of integrity issues, enabling timely interventions to prevent potential failures.

Table 14: Uses and limitations of different well logs for determining well integrity (*220*)

Methods	**Uses**	**Limitations**
CBL/VDL	Predicts well-bonded cement, debonding at wet casing, and formation	No prediction of mud channels, vertical cracks, gas chimney, and radial variation in cement
Ultrasonic imaging lag	Shows well-bonded cement, mud channel in good cement gas chimney, and debonding at wet casing	Unable to figure out mud channels in weak cement, vertical cracks, debonding at dry casing and formation, and radial variation in cement
Isolation scanner	Capable of showing good cement, mud channels gas chimney, thick vertical cracks, debonding at wet casing and formation, and cement radial variation	No prediction on thin vertical cracks and debonding at dry casing
RATS	Used to detect leaks	Incapable of predicting the quality of cement or casing
TL/acoustic log	Detects anomalies due to leak	No insight on cement
Corrosion log	Can predict the corrosion in the casing, tubular, and even casing after the cemented zone such as surface casing	No insight on cement
SAPT/VIT	Assessment of the hydraulic properties of the cemented annulus zone under study	No evaluation of cement and casing quality

Ugarte *et al.* concluded that while UHS presented a viable solution for large-scale energy storage, it introduced distinct challenges compared to UGS and CCS. Hydrogen's high diffusivity and reactivity demanded stringent design standards, material selection, and robust monitoring protocols to ensure long-term storage safety and operational security. Ongoing research and development were deemed necessary to enhance well integrity management in hydrogen storage applications (*220*).

A study by Wang *et al.* examined the feasibility of storing hydrogen in depleted unconventional gas reservoirs, which are typically reservoirs with low permeability, using a multiscale modeling approach that includes both pore-scale and reservoir-scale simulations (*228*). This study highlights the role of nanopores within unconventional reservoirs, where differential adsorption mechanisms allow methane to be preferentially retained. This adsorption effect creates a buffer that helps maintain hydrogen purity by limiting contamination from residual methane. Figure 60 illustrates how an increase in nanopore fraction improves the purity of produced hydrogen, emphasizing the critical role of nanopore systems in enhancing gas quality.

The research further investigates the impact of working pressure on storage capacity and hydrogen purity, noting that elevated pressures enhance hydrogen purity due to reduced methane diffusion into the hydrogen-rich areas (Figure 61). However, higher pressures necessitate more cushion gas, which can decrease overall storage capacity.

Figure 60: Comparison of the purity of the produced hydrogen at the end of the 3rd cycle with different nanopore fractions (*228*)

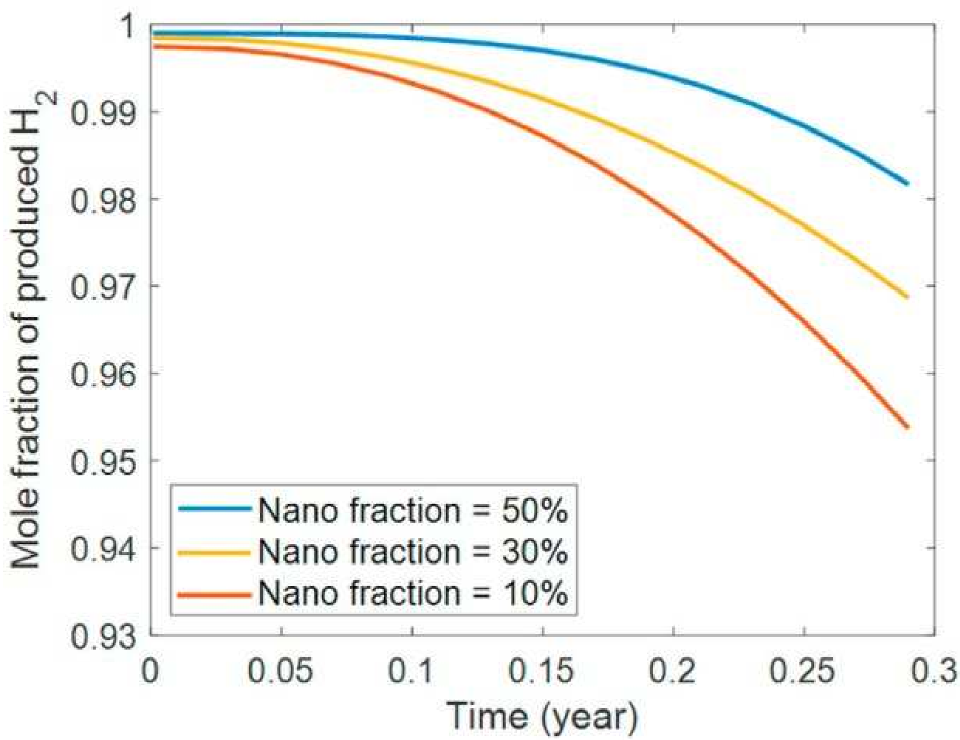
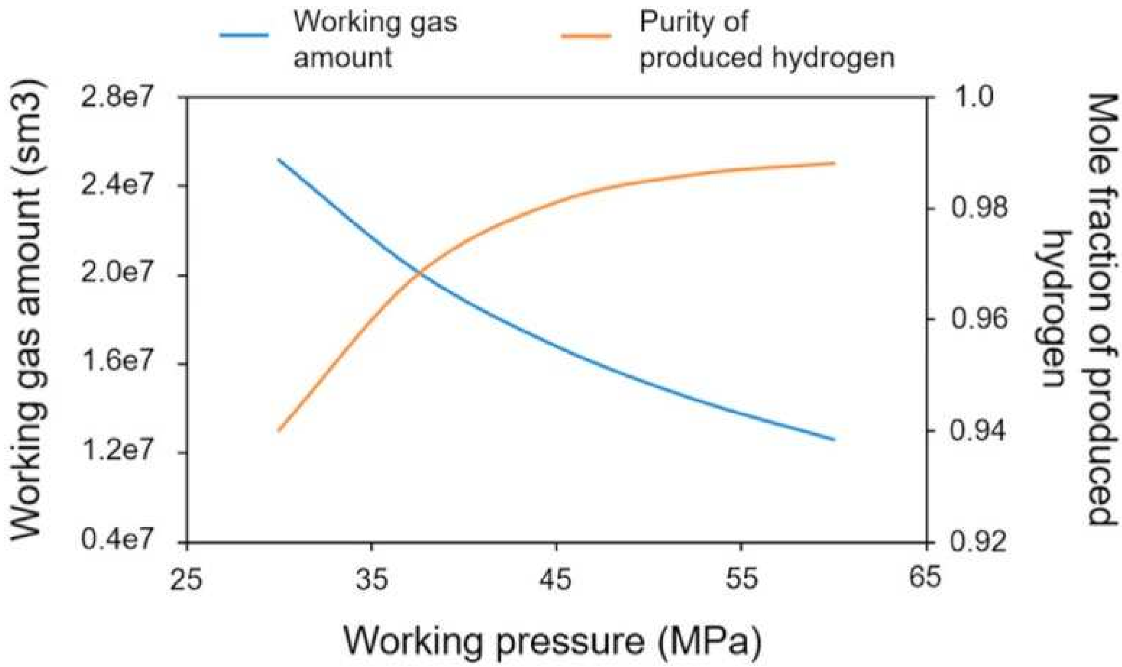


Figure 61: Variation of the amount of working gas and the purity of produced hydrogen with respect to the working pressure (*228*)



The findings indicate that unconventional reservoirs, particularly those with high nanopore volumes and adequate sealing properties, offer substantial potential for hydrogen storage. Effective storage also relies on managing pressure levels to balance gas purity and capacity. The study supports the importance of sealability in minimizing gas leakage risks, especially as unconventional reservoirs may have fewer venting channels due to limited vertical wells compared to conventional fields. Wang *et al.* concluded that the potential for hydrogen storage in such formations depends on various factors, including nanopore volume, reservoir permeability, and geological integrity, which must be optimized to ensure safe and efficient storage. Further research is recommended for large-scale applications (*228*).

Epelle *et al.* examined the potential for underground hydrogen storage in geological formations, emphasizing the technical challenges associated with ensuring safe and effective storage (*229*). Epelle *et al.* note that, while depleted oil and gas reservoirs offered favorable storage conditions, hydrogen's reactivity with certain reservoir rock minerals could trigger geochemical changes that might weaken sealability over time. These interactions, they explained, could lead to mineral dissolution and the formation of micro-fractures, potentially allowing hydrogen to escape. The study underscored the need for continued research on material compatibility and the long-term integrity of well casings and sealing materials under the cyclic loading associated with hydrogen injection and extraction. By addressing these well integrity issues, they concluded, advancements in underground hydrogen storage could enhance safety and reliability, positioning depleted reservoirs as viable options for large-scale hydrogen storage (*229*).

Microbial response and other challenges

Aslannezhad *et al.* analyzed technical challenges in underground hydrogen storage, with a specific focus on microbial responses such as methanogenesis (*230*). Microbial activity, particularly from hydrogenotrophic methanogens, emerged as a critical issue, as these microbes consume stored hydrogen and generate methane, which reduces hydrogen purity and complicates recovery. Muhammed *et al.* confirmed that this microbial-induced methane production could decrease UHS efficiency by introducing contaminants, thus raising purification costs and operational complexity (*219*). Similarly, Ugarte *et al.* emphasized microbial corrosion and hydrogen sulfide production by sulfate-reducing bacteria as additional concerns. Hydrogen sulfide, known for its corrosive properties, exacerbates well integrity issues by degrading steel casings and other storage infrastructure (*220*).

Zeng *et al.* noted that biofilms produced by SRB and iron-reducing bacteria (IRB) pose another challenge by clogging pore spaces and promoting microbial-induced corrosion (MIC), resulting in a weakening of wellbore materials over time (*228*). They illustrated that biofilm formation not only obstructs hydrogen flow but also accelerates infrastructure deterioration, as SRB-generated H_2S further enhances corrosion rates. In cases studied by Raza *et al.*, such biofilms also reduced permeability near the wellbore, impeding hydrogen injectivity and withdrawal infrastructure (*231*). Muhammed *et al.* discussed how microbial activity, including H_2 consumption by SRB and IRB, could contribute to hydrogen loss, undermining storage purity and containment (*218*).

Table 15 compares different subsurface storage media, including depleted gas reservoirs, by evaluating parameters such as storage capacity, injectivity, and withdrawal cycles, which are critical in decision-making for UHS applications (*218*). This comparison underscores the importance of selecting reservoirs with robust structural and microbial resistance properties.

Table 15: Different utility-scale subsurface storage and aspects considered during decision-making (*218*)

	Salt cavern	Aquifer	Depleted oil and gas
Point in development	Commercial	Laboratory	Laboratory
Number of injection/withdrawal cycles	Up to 10	1 to 2	1 to 2
Storage capacity (tonnes of H_2)	Small to Medium (1000 – 3500)	Large to Very Large (7200 – 53,000)	Medium to Large (2000 – 23,000)
Cushion gas percentage	20 to 33	45 to 80	50 to 60
Operating pressure (bar)	45 to 202	30 to 137.8	100 to 400
Rate of discharge (GW/day)	0.467 to 10.128	1.09 to 8.55	2.66 to 100

Muhammed *et al.* further emphasized risks to well integrity, particularly related to cement degradation, as exposure to hydrogen and byproducts like carbon dioxide and hydrogen sulfide, could increase cement porosity and permeability, potentially leading to gas leakage. These findings highlight the need for durable wellbore materials and advanced monitoring systems to maintain UHS safety and operational efficiency, particularly in depleted reservoirs where microbial challenges and structural integrity are paramount (*218*).

Research has identified various technical and microbial challenges in UHS, particularly in depleted gas reservoirs. While hydrodynamics, geochemistry, and microbial activity have been explored, there is limited understanding of the geomechanical effects of cyclic hydrogen injection and withdrawal in these reservoirs (*225*). Further studies are needed to assess how repeated pressurization cycles may affect reservoir integrity, potentially impacting hydrogen retention over extended periods (*220*). Al-Shafi *et al.*

discussed challenges unique to hydrogen storage, comparing containment and microbial responses between natural gas and hydrogen systems. They highlighted that hydrogen's low molecular mass poses distinct challenges for underground storage, often requiring additional cushion gas to stabilize pressure for efficient injectivity and withdrawal (*232*).

This chapter highlights the intricate challenges of UHS, ranging from microbial-induced corrosion and material degradation to the critical issues surrounding well and caprock integrity. Hydrogen's high mobility and reactivity, along with its complex interactions with geological formations and infrastructure, necessitate continuous monitoring, innovative sealing technologies, and carefully tailored operational approaches. Mitigating the risks associated with hydrogen embrittlement, microbial activity, and geochemical reactions is essential to ensuring the long-term safety, efficiency, and sustainability of underground hydrogen storage systems.

LIST OF ACRONYMS

Term	Definition
ABS	Acrylonitrile Butadiene Styrene
ANN	Artificial Neural Network
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
BOS	Background Oriented Schlieren
CBL	Cement Bond Log
CCHP	Combined Cooling, Heat, and Power
CCS	Carbon Capture and Storage
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPM	Computational Pipeline Monitoring
CPUC	California Public Utilities Commission
CRAs	Corrosion-Resistant Alloys
DGR	Depleted Gas Reservoir
DLE	Dry Low Emission
DU	Dobson Unit (a measure of ozone concentration)
EPA	Environmental Protection Agency
EPDM	Ethylene Propylene Diene Monomer Rubber
EVOH	Ethylene Vinyl Alcohol
FDT	First Dangerous Time
FKM	Fluorocarbon Rubber (Vinylidene fluoride)
GCV	Gross Calorific Value
GWP	Global Warming Potential

Term	Definition
H_2	Hydrogen
H_2S	Hydrogen Sulfide
HAZ	Heat-Affected Zone
HBNG	Hydrogen Blended Natural Gas
HBR	Hydrogen Blending Ratio
HDPE	High-density Polyethylene
HENG	Hydrogen Enriched Natural Gas
HNBR	Hydrogenated Nitrile Butadiene Rubber
HO_2	Hydroperoxyl Radical
IR	Individual Risk
IRB	Iron-Reducing Bacteria
JTC	Joule-Thompson Coefficient
LDPE	Low-density Polyethylene
LFL	Lower Flammability Limit
MIC	Microbial-Induced Corrosion
MILD	Moderate or Intense Low-oxygen Dilution
NBR	Nitrile Butadiene Rubber
NBR-CB	Nitrile Butadiene Rubber with Carbon Black
NBR-SC	Nitrile Butadiene Rubber and Silica
NETL	National Energy Technology Laboratory
NG	Natural Gas
NO_X	Oxides of Nitrogen
O_3	Ozone
OH	Hydroxyl Radical
PA	Polyamide
PA11	Polyamide 11
PA12	Polyamide 12

Term	Definition
PA6	Polyamide 6
PEGDGE	Poly(ethylene glycol) Diglycidyl Ether
PPI TR	Plastics Pipe Institute Technical Report
ppm	Parts Per Million
ppt	Parts Per Trillion
PTFE	Polytetrafluoroethylene
PVA	Polyvinyl Alcohol
PVC	Poly Vinylidene Chloride
QRA	Quantitative Risk Assessment
RDL	Readily Detectable Level
SEM	Scanning Electron Microscopy
SRB	Sulfate-Reducing Bacteria
Tg	Teragram (one trillion grams)
THT	Tetrahydrothiophene
TROPOS	Tropospheric Chemistry-Transport Model
UC	University of California
UGS	Underground Gas Storage
UHMWPE	Ultra-high-molecular-weight Polyethylene
UHS	Underground Hydrogen Storage
UKESM1	United Kingdom Earth System Model
VDL	Variable Density Log
WCL	Weld Center Lines
WI	Wobbe Index

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