Compatibility Assessment of Natural Gas Pipeline Infrastructure Materials with Hydrogen, CO_2, and Ammonia

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Project Goals

- Overarching goal is to determine whether existing natural gas pipeline infrastructure can be repurposed for use with hydrogen, carbon dioxide and/or ammonia. To be achieved by:
  - Assessing the known compatibilities of existing natural gas (NG) pipeline transmission system materials with hydrogen and its blends with NG, carbon dioxide, and ammonia
  - Identifying which materials and components are suitable for use with hydrogen, carbon dioxide and/or ammonia and determine at risk systems.
- Provide a report detailing infrastructure material compatibility and data gaps.

Overview

Timeline

- Project State Date: 5/01/2021
- Project End Date: 3/31/2023
- Percent Complete: 100%

Barriers

- Capital/transportion cost
- System efficiency
- Safety

Budget

- Total Funding Spent: $500k
- Total DOE Project Value: $500k

Collaborators

- State of Minnesota, Department of Commerce
- Xcel Energy
- CenterPoint Energy
- Hawai'iGas

Relevance and Potential Impact

Project provides immediate assessment of natural gas pipelines for hydrogen, carbon dioxide, and ammonia transport and identifies pathways to implementation

Relevant DOE Goals

- Lower greenhouse gas emissions by facilitating hydrogen and CO_2 transport
- Repurposed existing infrastructure accelerates and reduces costs to build clean energy infrastructure

Potential Impact:

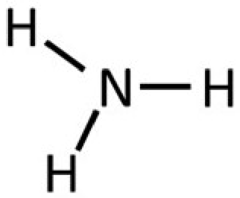
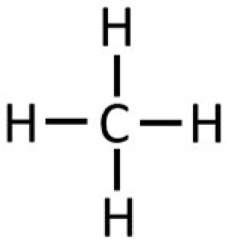
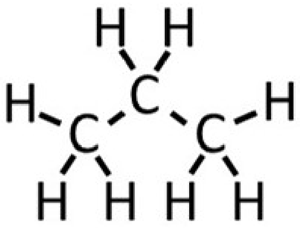
- Rapid/immediate integration of hydrogen as a clean fuel thereby reducing carbon emissions.
- Accelerates CO_2 sequestration by using an existing pipeline network to move carbon

Potentially quicker and lower cost pathway to facilitating hydrogen and CO_2 transport, and therefore accelerates GHG reduction

Approach

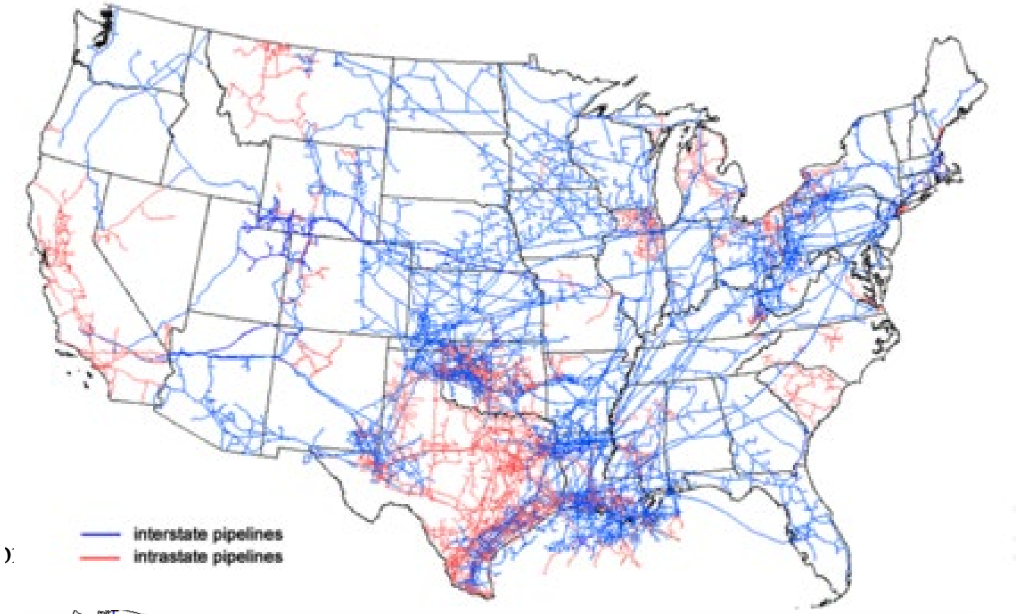
- Conduct a comprehensive assessment to include materials of construction for pipelines and compressor/regulator stations
- Out-reach and discussions with Hydrogen Materials Compatibility Consortium (HMAT) leadership
- Data sources included industry partners, manufacturer specification sheets, extensive compatibility literature
- Partnerships with Xcel Energy, HawaiiGas, and CenterPoint Energy
- Assessment to focus on physical/chemical properties of gas chemistries, operational boundaries of system/component, material application (under active stress or not). Water contamination was included in the analysis, but not other impurities.

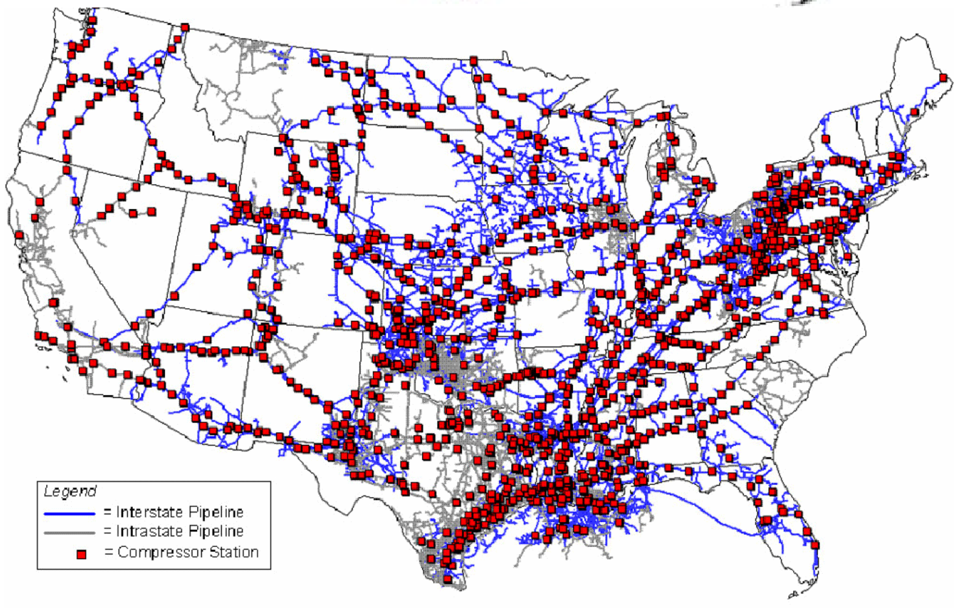
Fluid properties relevant to compatibility

Gas/fluid type	Structure	Polarity	Solubility in water at 20°C and 1 atm (g/kg_{water})
Hydrogen		Nonpolar	0.0016
Carbon dioxide		Polar	1.69
Ammonia		Highly polar	529.0
Methane		Nonpolar	0.023
Propane		Nonpolar	0.0047 (at 0°C)

Quickest, most efficient and cost-effective means of transporting fuels and/or CO_2 is to repurpose existing natural gas (NG) pipeline infrastructure

- Over 300,000 miles of natural gas transmission pipelines and 1800 compressor stations in the continental U. S.
- These pipes can have diameters up to 1.2 m (48 in.) and are composed almost entirely of low-carbon steels, though some cast, ductile, and wrought irons are still in use.
- The gauge pressure in these systems can range from 1.4 to 10.3 MPa (200 psi to 1,500 psi). For most transmission systems the line pressure is relatively constant
- Pipes are designed with safety factors of 1.25 or 1.5 depending on the population density





Previous and current repurposing compatibility studies have focused solely on the piping sections

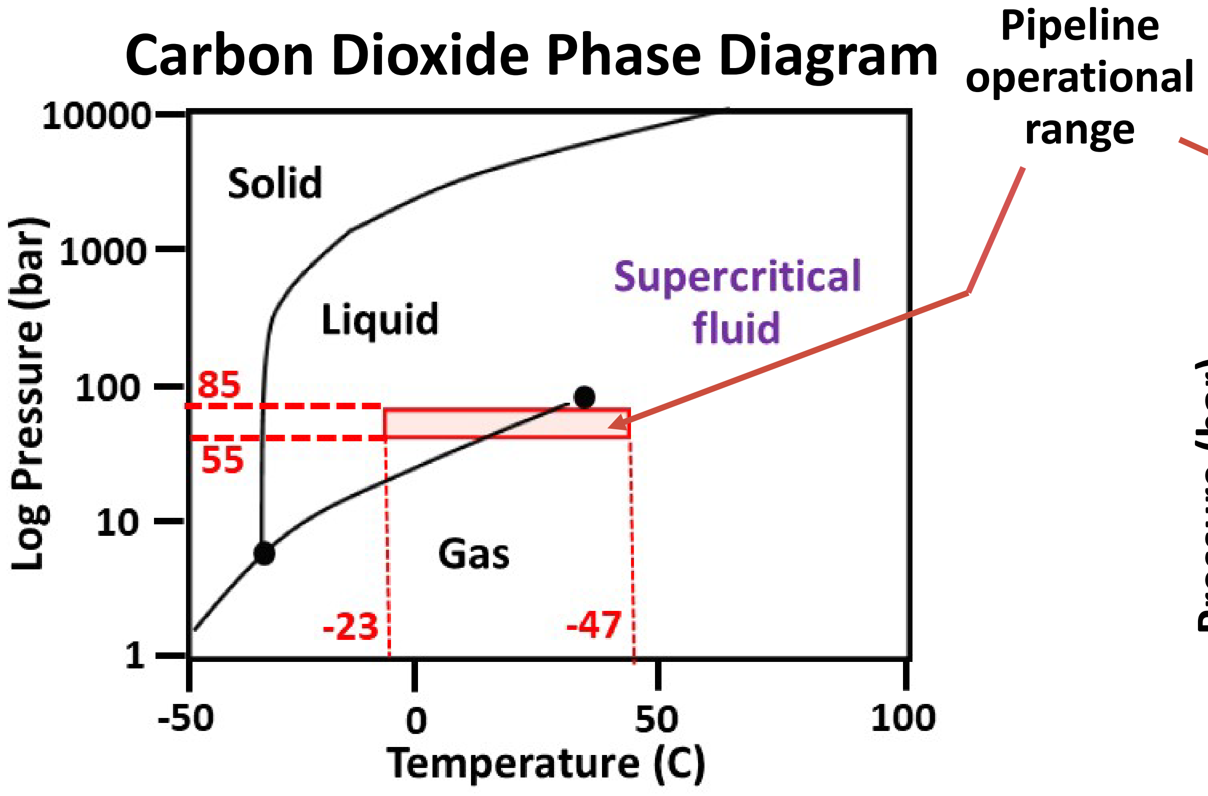
Approximately 1800 compressor stations

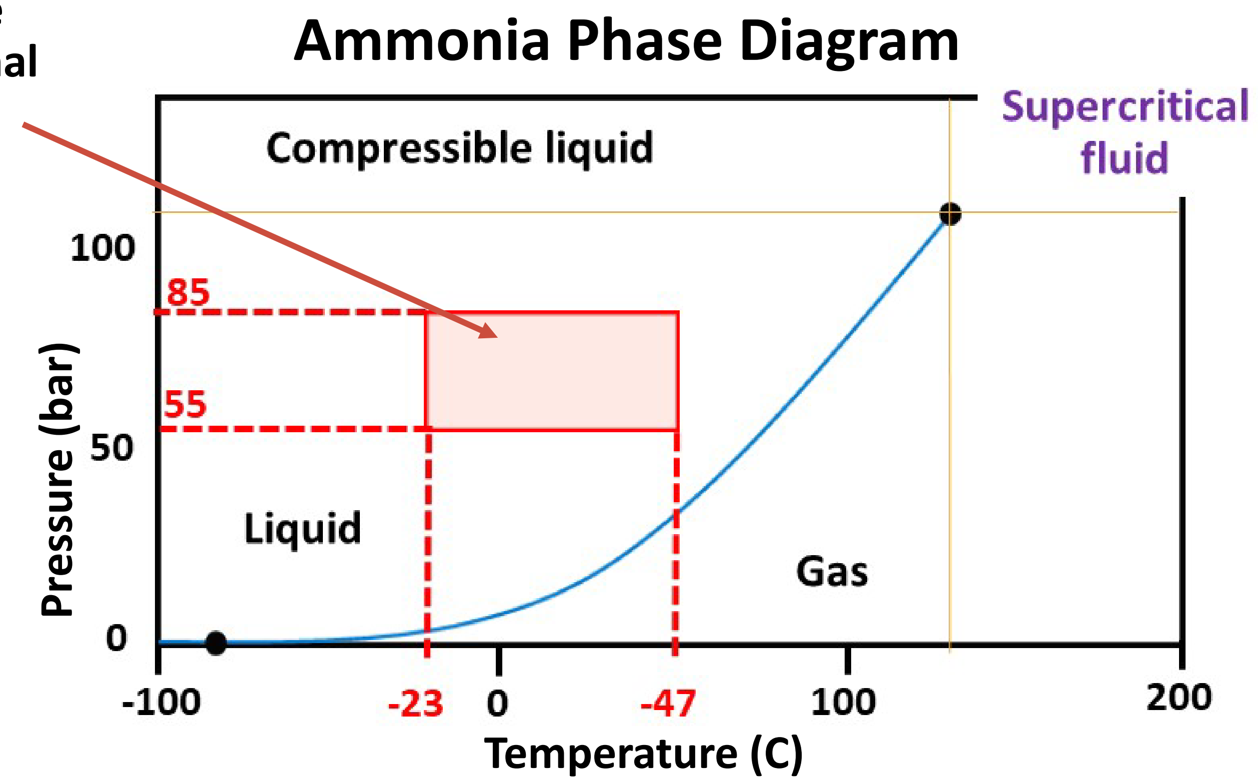
A lot more going on here

- API steel grades: A25, A, B, X42, X52, X60, XC60, X70, X80 and X100
- Seamless or welded
- Many pipes have an inner epoxy coating to reduce friction and wear (and also corrosion)
- Numerous compatibility studies with hydrogen

- Consists of compressors, odorant inputs, gages, valves, meters, regulators, etc
- Many different components containing a variety of ferrous and nonferrous metals and polymers (plastics and elastomers)
- Very little compatibility studies with hydrogen

Under the typical range of NG pipeline operation (55-85 bar), hydrogen exists as a gas, but this is not true for CO_2 and ammonia





- Gas or liquid phases depending on temperature
- Not a region that is well-studied
- Impurities will be a factor

- Ammonia in liquid phase
- Ammonia should be compatible with most NG pipelines

What we know about H_2 compatibility

For Metals: H_2 embrittlement of pipeline steels has been extensively studied.

- ASME B31.12 recommends maximum grade of X52 & API guidelines call for a maximum yield strength of 827 MPa
- Studies suggest that NG blends containing up to 17% H_2 are suitable for use in existing NG pipelines

For Polymers: Much less studied, especially at conditions accompanying NG pipelines.

- Operational experience with NG-hydrogen blends indicates suitability with existing infrastructure elastomers and plastics
- High swell observed for some elastomers under high pressures.
- Blister damage due to high decompression is a concern

Important knowledge gaps include:

- Many compressor station polymers not evaluated, especially at pipeline conditions
- Key information pertaining to the specific steel and alloy grades in compressor station components is not available.
- The loads and stresses that are placed on stressed metal components (e.g. springs, diaphragms, etc.) in compressor stations during operation are not available.

What we know about CO_2 compatibility

For Metals: Extensive body of literature exploring CO_2 corrosion of pipeline steels.

- Corrosion requires the presence of aqueous condensate (carbonic acid is formed)
- Studies have shown that H_2O, H_2S, SOx and O_2 can accelerate corrosion. Less well understood are NOx contributions, which is a primary product of combustion. Note that NOx will form nitric and/or nitrous acid with water.

For Polymers: Much less studied, especially at conditions accompanying NG pipelines.

- Known solvent for some polymers
- High swell observed for some elastomers
- Limited range of polymers studied

Important knowledge gaps include:

- Contribution of impurities (including NOx) to aqueous corrosion
- Corrosivity in liquid and gaseous CO_2 at conditions below the critical point
- Aluminum, stainless steels, zinc, brass, and other steel grades that are used extensively in compressor/regulator stations
- Many compressor station polymers not evaluated, especially at pipeline conditions

What we know about ammonia compatibility

For Metals: Extensive body of literature on ammonia compatibility with metals. Ammonia is used extensively in agricultural applications, as such storage and handling infrastructure is well established.

- Anhydrous ammonia is compatible with stainless steel grades, but low carbon, low-allow steels are susceptible to stress corrosion cracking if oxygen is present.
- Anhydrous ammonia is also suitable for use with copper-containing alloys. However, minor amounts of water will enable stress corrosion cracking.

For Polymers: Extensive body of literature on ammonia compatibility with polymers

- Ammonia compatibility standards exist: ANSI B31.3 and ANSI K61.1
- Incompatibilities exist with fluorocarbons, polytetrafluoroethylene (PTFE), styrene butadiene rubber (SBR).
- Suitability of ammonia with polyurethane and epichlorohydrin rubber is questionable
- Compatible polymers include some acrylonitrile butadiene rubbers (NBRs), nylons, and neoprene

Accomplishments and Progress: Completed assessment

- Study examined materials compatibility of repurposing NG infrastructure for H_2, CO_2 and/or NH_3 transport
  - Material compatibility performance based on available literature studies
    - Study looked at compressor/regulator stations
    - Identified over 100 components and materials of construction
  - GIS analysis of pipelines
  - Identified key gaps

- Kass, M. D., Keiser, J. M. et al., "Assessing Compatibility of Natural Gas Pipeline Materials with Hydrogen, CO2, and Ammonia," *J. Pipeline Syst. Eng. Pract.*, 2023, 14(2): 04023007

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Assessing Compatibility of Natural Gas Pipeline Materials with Hydrogen, CO_2, and Ammonia

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Abstract: In this study, we examine the efficacy of repurposing natural gas (NG) pipelines for transporting hydrogen blends (with NG), ammonia, and CO_2 (gaseous and supercritical) from the standpoint of materials compatibility. Some information pertaining to component performance is also included, especially those components critical for pressurization and monitoring of flow. A listing of critical pipeline components and materials was developed, and their compatibilities was assessed for each fluid or gas type based on known compatibilities. Results indicate that pipeline materials should be suitable for gaseous CO_2 and anhydrous ammonia, but hydrogen blends greater than 12% may be problematic. Current compressor/regulator stations will not be suitable for use with either supercritical CO_2 or ammonia. Important knowledge gaps were identified, including (1) polymer performance with hydrogen/NG blends at low pressures, (2) compressor/regulator station polymers and epoxy coating materials with supercritical CO_2, and (3) metal performances of hydrogen/NG blends at low pressures.
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Introduction

Background

Natural gas (NG) pipeline systems consist of transmission lines, distribution lines, and compressor/regulator stations with approximately 3 million miles of pipelines used to transport and distribute natural gas in the United States (USEIA 2022). This extensive infrastructure was largely built over a period of 80 years, spans the continental United States, and represents a massive investment that supports the delivery of energy across the nation. As our energy systems transition from using traditional hydrocarbon resources to more renewable and nuclear sources there will likely be a need to transport other fluids at scales approaching our current natural gas system both to reduce atmospheric levels of carbon and as alternative energy carriers. Repurposing our existing NG pipeline system offers a potentially less expensive and more rapidly deployed approach for transporting large volumes of hydrogen (as blends with NG), ammonia, or CO_2 (supercritical and gaseous), but the feasibility of using the system to transport alternative fluids requires assessing the compatibility of the materials in the system with the alternative fluids.

A listing of the structures and relevant properties of hydrogen, CO_2, and ammonia is shown in Fig. 1 along with methane (the primary component of natural gas). Carbon dioxide, ammonia, and methane are relatively small molecules, but, unlike hydrogen, they are too large to diffuse through metals. However, permeation does occur with many polymers. Here it is a function of molecular size (diffusivity) and the van der Waals forces (which includes polar contributions) between the fluid molecule and the solid polymer. As shown in the table, hydrogen and methane are nonpolar, while both CO_2 and ammonia are polar. Water solubility is another important characteristic since water is a major contaminant in pipelines and the dissolution of chemical species (into water) can contribute to aqueous corrosion in steels if acids are formed. Both hydrogen and methane are relatively insoluble in water, CO_2 is moderately soluble, and ammonia is highly soluble. The dissolution of CO_2 into water will lower the pH due to the formation of carbonic acid, while ammonia, in marked contrast, will raise the pH.

Approximately 300,000 mi of transmission lines are used to move NG over long distances (Schmura et al. 2005). These pipes can have diameters up to 1.2 m (48 in.) and are composed almost entirely of low-carbon steels, though some cast, ductile, and wrought irons are still in use. The gauge pressure in these systems can range from 1.4 to 10.3 MPa (200 psi to 1,500 psi) (Schmura et al. 2005). For most transmission systems the line pressure is relatively constant; however, some pipeline companies do not have separate storage facilities and use the transmission piping itself for overnight storage. For these systems the pressure can increase by several MPa (100 psi) during low usage. Distribution lines transport the natural gas at gauge pressures <0.7 MPa (<100 psi) to homes and residential use. These pipes are smaller in diameter and are typically composed of either steel or plastic (polyethylene, polyvinyl chloride, or polyamide). Because of its lower cost and versatility, polyethylene is becoming more predominant in distribution systems. In addition to the pipes themselves, existing NG systems include compressor stations which contain, not only compressors, but also regulators, meters, valves, and other components composed of various polymers and both ferrous and nonferrous metals. These subunits of the compressor station are also expected to be in contact with, and therefore compatible with, the flowing gas or fluid. There are also regulators and meters to

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Pipeline Assessment

- Existing NG pipelines likely suitable for low blend levels of hydrogen (in NG), *gaseous* carbon dioxide, and ammonia
- Impurities will be important, especially if switching between fluid chemistries
- Need to consider not just material but component performance
- Obtaining precise material information can be challenging

Compressor station materials compatibility performance was assessed and tabulated for metal and polymer components

- Fuel chemistries included H_2, low level H_2 blends (with NG), carbon dioxide, and ammonia
- Compatibility for each material class (metal and polymer) ranked as suitable, incompatible or questionable. (Example on right for metals only.)
- ***Compressor stations are not suitable for use with neat hydrogen, supercritical CO_2 or ammonia***

Abbreviated listing of compressor station metals and predicted compatibilities with hydrogen, CO_2, and ammonia

Component	Sub component	Material	100% Hydrogen or High Blend Levels	Low-level Hydrogen Blends	sCO2	Ammonia	Comments
Plug Valve	Full assembly	Cast iron	Incompatible	Questionable	Suitable	Suitable	
Ball valve	Entire valve assembly	Brass	Suitable	Suitable	Suitable	Incompatible	
		301 Stainless steel	Suitable	Suitable	Suitable	Suitable	
		Carbon steel	Incompatible	Questionable	Suitable	Suitable	
Safety shut valve	Casting	Iron	Incompatible	Questionable	Suitable	Suitable	
		Steel	Incompatible	Questionable	Suitable	Suitable	
	Diaphragm casings	Aluminum	Incompatible	Questionable	Suitable	Suitable	
		Steel	Incompatible	Questionable	Suitable	Suitable	
	Diaphragm plates	Steel	Incompatible	Questionable	Suitable	Suitable	Critical component under high stress
	Orifice	Brass	Incompatible	Suitable	Suitable	Incompatible	
		Steel	Incompatible	Questionable	Suitable	Suitable	
	Fasteners	Steel	Incompatible	Questionable	Suitable	Suitable	
	Springs	Steel	Incompatible	Questionable	Suitable	Suitable	Critical component under high stress
	Cap	Aluminum	Incompatible	Questionable	Suitable	Suitable	
Appliance regulators	Housing	Cast iron	Incompatible	Questionable	Suitable	Suitable	
		Aluminum	Incompatible	Questionable	Suitable	Suitable	
		Brass	Suitable	Suitable	Suitable	Incompatible	
	Vent emitters	Brass	Suitable	Suitable	Suitable	Incompatible	

Full table listings available in published manuscript

Remaining Challenges and Barriers

- For technology acceleration and data collection:
  - Specific, more precise material composition needed to accurate confirm performances
  - Industry feedback needed to better identify system components or anomalies that were missed
  - Experimental work to address information gaps
- For industry acceptance and implementation:
  - Joint efforts using existing pipelines is needed to completely performances
  - Industry test beds will be coming on-line in the next year. Novel specimen designs and test fixtures will need to be considered.

Recommended Future Work

- Obtain more precise operational and material information from industry
- Determine whether existing pipeline safety factors are acceptable
- Improved understanding of impurities and their contributions to hydrogen corrosion, especially at NG pipeline conditions. Field studies currently being proposed with energy companies.
- Improved understanding of impurities and their contributions to carbon dioxide corrosion, especially at NG pipeline conditions
- Address key data gaps associated with sCO_2 and polymer compatibility
- Assess existing component performance (i.e. meters, valves, etc.) with hydrogen blends, carbon dioxide and ammonia.
- Determine which NG pipelines have the best near-term prospects for repurposing.

Summary

- ***Relevance:*** Effort advances the transport of hydrogen, carbon dioxide and ammonia by identifying opportunities and challenges of repurposing NG pipeline infrastructure
- ***Approach:***
  - Conducted extensive literature data survey
  - Examined over 100 components and materials in pipeline infrastructure
  - Performance ranked based on known compatibilities
- ***Collaborations:*** HawaiiGas, Xcel Energy, CenterPoint Energy, MN Department of Commerce
- ***Technical Accomplishments:***
  - Identified and evaluated compatibility with over 100 infrastructure components and materials of construction
  - Determined that NG pipelines are likely suitable for use with low blend levels of hydrogen, gaseous carbon dioxide and ammonia
  - Compressor stations will not be compatible with neat hydrogen, sCO_2 and ammonia
  - Identified key knowledge gaps