Databasing information for existing pipeline infrastructure / Dual-use infrastructure – technical considerations for dual-use transport of LPG/LNG/H_2/CO_2/Ammonia

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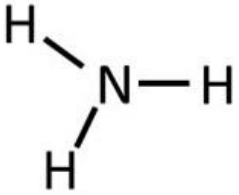
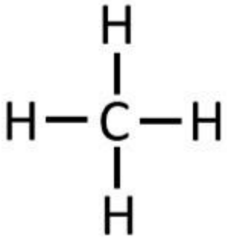
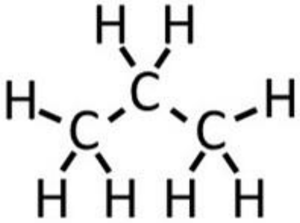
As we see it, there are two primary questions regarding dual purposing:

- Can existing natural gas (NG) pipelines be repurposed for hydrogen, CO_2 and/or ammonia?
- Can liquefied natural gas (LNG), liquid petroleum gas (LPG), and ammonia infrastructure be repurposed for CO_2 and hydrogen (or ammonia)?

Technical considerations based on:

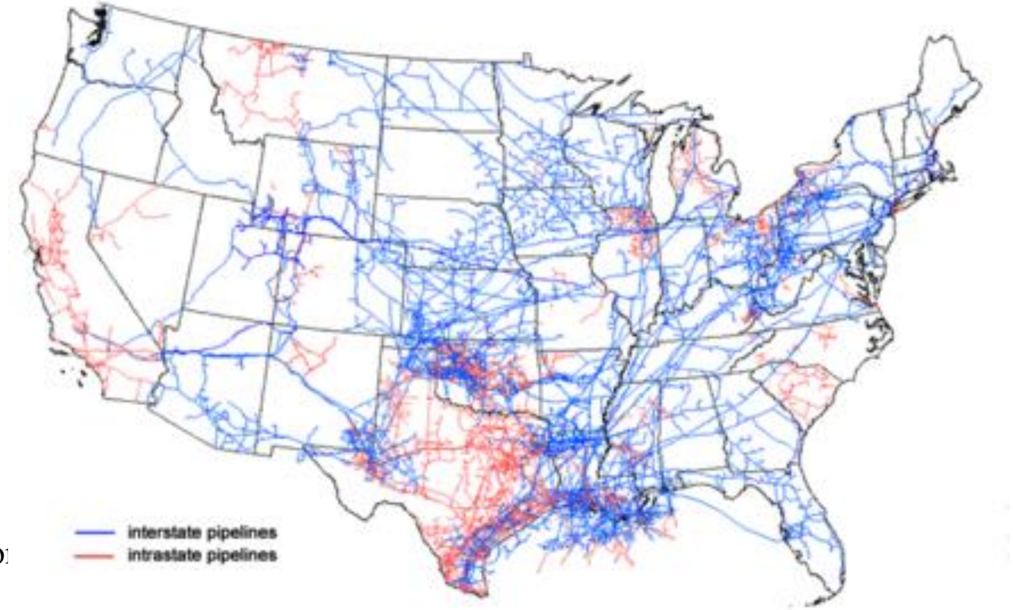
- Compatibility with infrastructure materials and component performance (includes impurities)
- Desired physical state (liquid or gas)

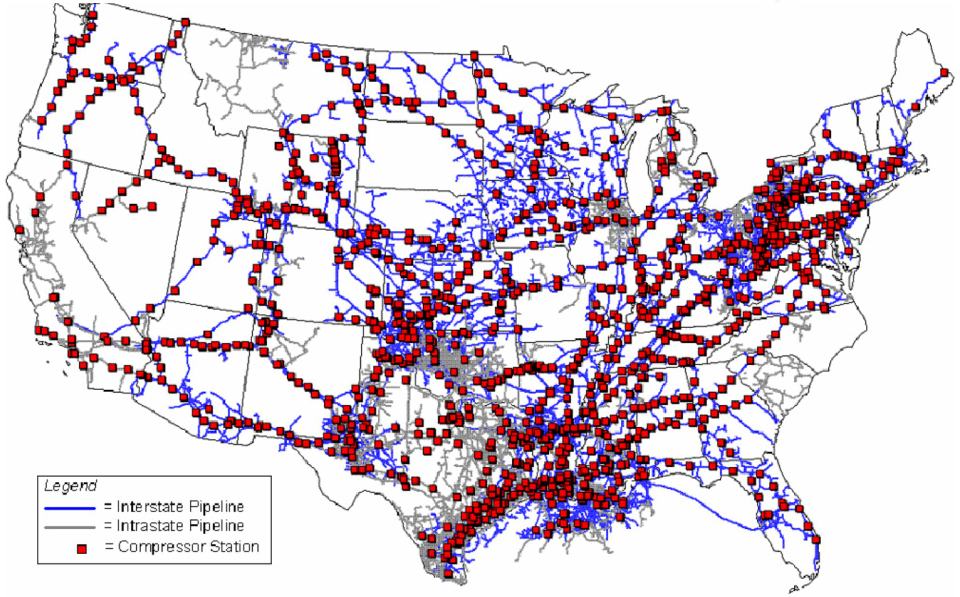
Fluid properties relevant to compatibility

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

280,000 miles of transmission pipes

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

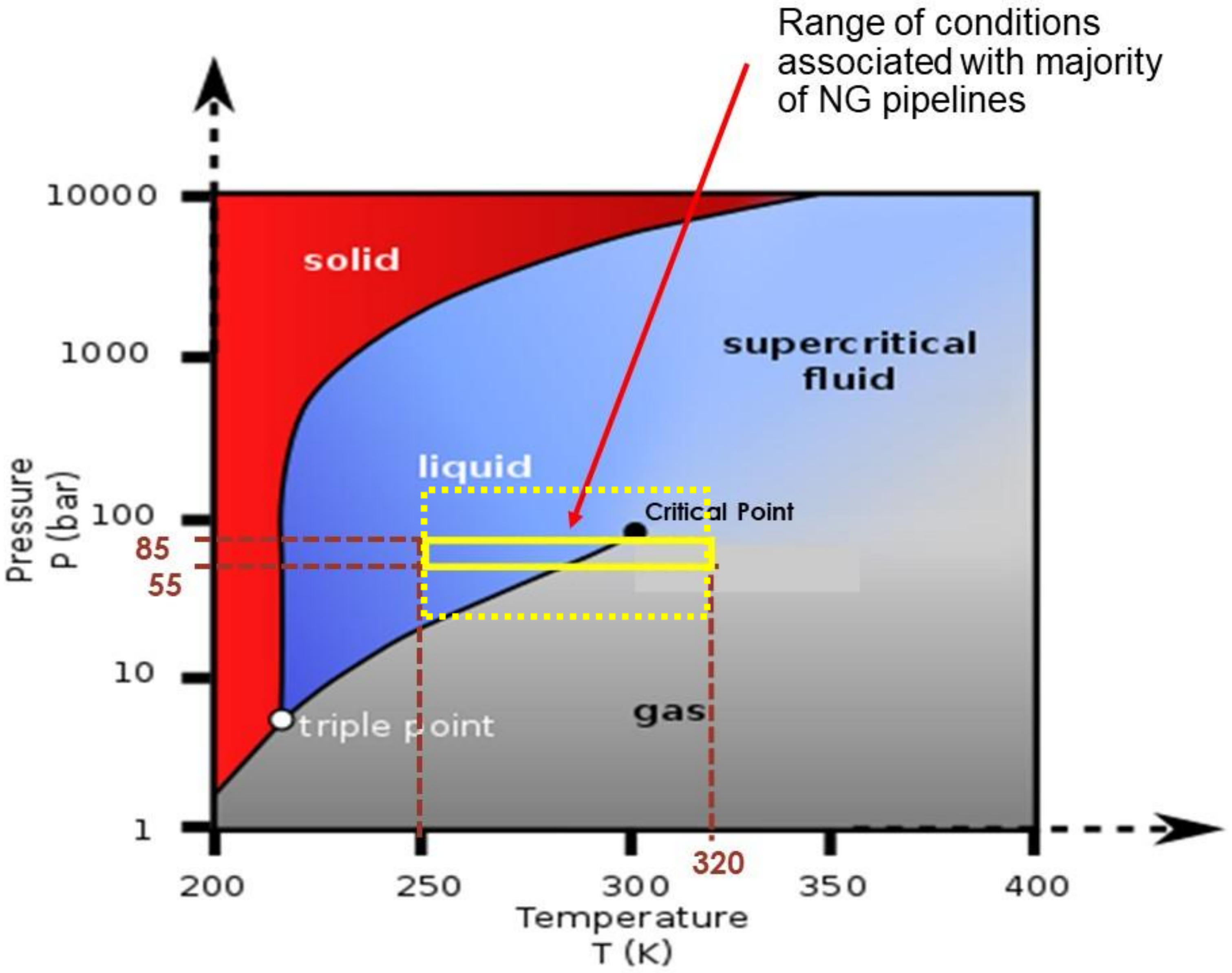
- Consists of compressors, odorant inputs, gages, valves, meters, regulators, etc
- Many different components containing a variety of ferrous and nonferrous metals and polymers (plastics and elastomers)
- Very little compatibility studies with hydrogen

Hydrogen transport in NG pipelines

- Hawai'iGas has been transporting 10-12% H_2 in its pipelines for the past 50 years
- Several field demonstrations are being established by pipeline manufacturers to evaluate H_2 blends with NG
- General assessment that blends less than 10% are suitable for most pipeline steel grades. Lower yield strength steels are mandated:
  - ASME B31.12 recommends maximum grade of X52
  - API Guidelines call for a maximum yield strength of 827 MPa (120ksi)
- Impurities can accelerate stress corrosion cracking
- Impacts of impurities on polymer performances at NG pipeline conditions is not well known
- End use systems may not operate properly with hydrogen blends. This is also true for infrastructure components (e.g. flow meters)

The majority of NG pipelines operate under conditions slightly below the CO_2 critical point

- Typical range is 800-1,000psi, but some systems operate up to 1,500psi (103bar) and down to 200psi (13.8bar)
- Gas or liquid phases fluctuate depending on temperature
- Existing CO_2 pipelines operate above 1,900psi (130bar)
- Not a region that is well-studied, especially for addressing impurity impacts
- Netherlands repurposed a 26 inch, 51-mile NG pipeline for CO_2 transport as a gas at 101-304psi (7-21bar) at a rate of 300Mt/year



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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.

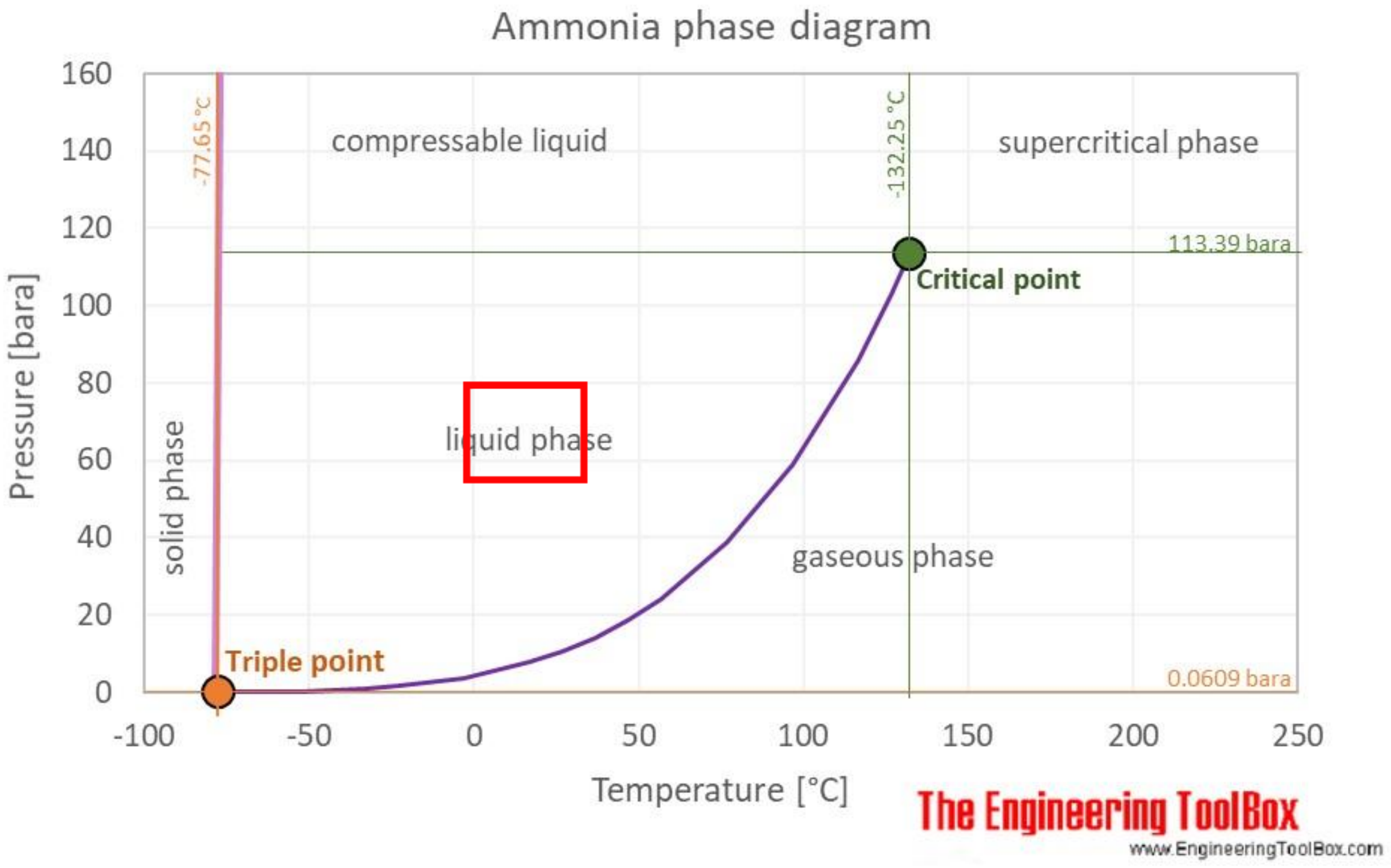
- Known solvent for some polymers
- High swell observed for some elastomers
- Limited range of polymers studied

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

NG Pipelines: Ammonia would primarily exist as liquid

- Ammonia is widely and safely transported ***in systems specifically designed for handling ammonia***.
- NG pipeline steels are suitable for ammonia
- Oxygen impurities can promote stress corrosion cracking
- Ammonia transport via NG pipeline sections is feasible, but compressor stations are not suitable. Fluorocarbons (FKMs) and some NBRs are not suitable.



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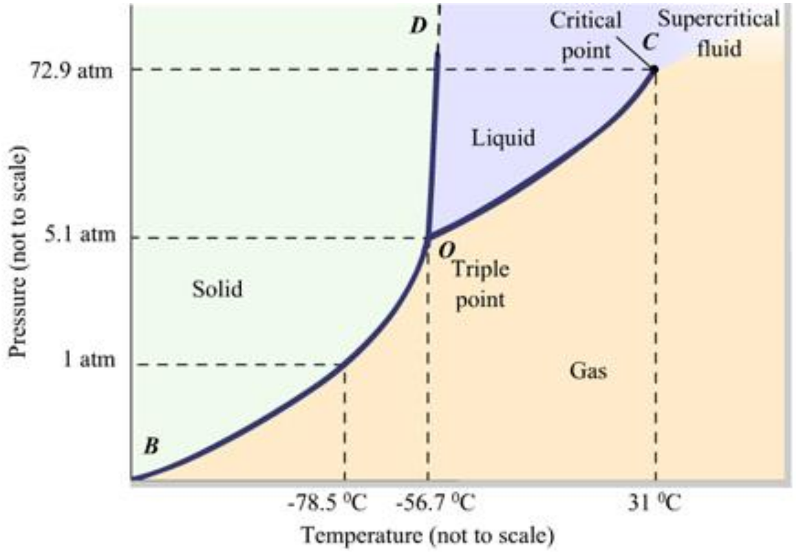
Repurposing LNG or LPG infrastructure for sCO_2 , hydrogen, or ammonia.

- LNG/LPG conditions
  - LNG tanks are maintained at -161.5°C (-260°F) and 0.34 bar (5 psi)
  - LPG is typically stored at pressures up to 1.7 bar (25 psi) and ambient temperature
- ***H_2***: Liquefying and shipping hydrogen requires chilling it to -253 degrees Celsius. Nearly 100 Celsius degrees colder than temps needed to transport LNG
- ***sCO_2***: CO_2 cannot liquefy in LNG and LPG tanks (pressure too low)
- ***Ammonia***: will exist as liquid in LNG and LPG systems
- Other considerations include inherent impurities and the high solvency of sCO_2 with many elastomers

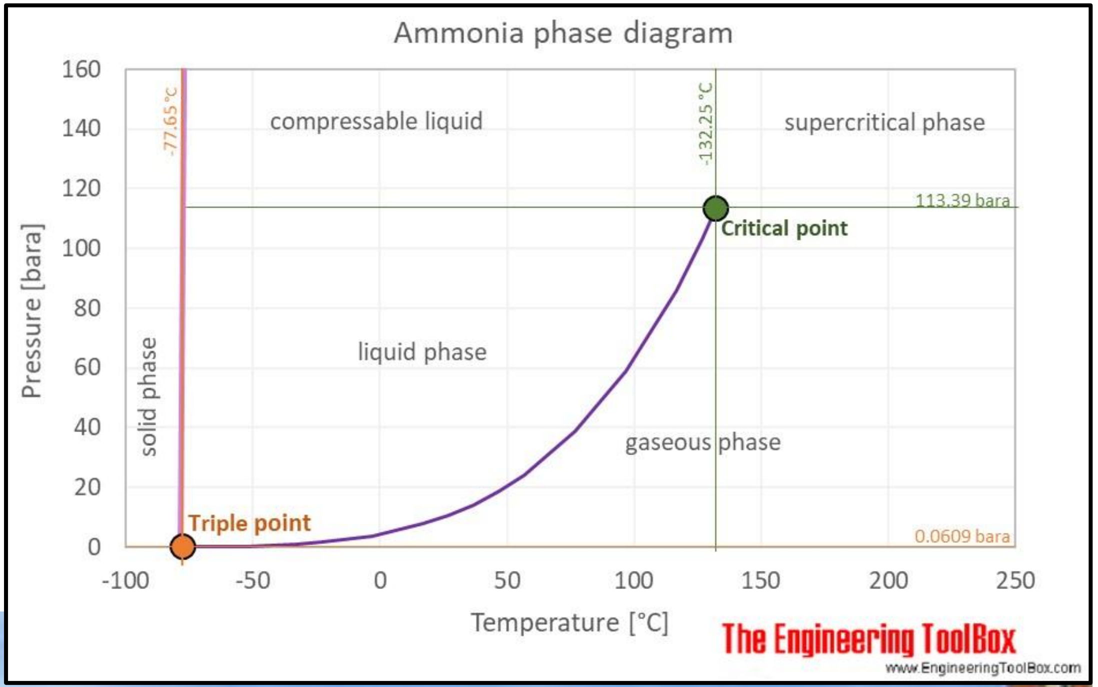
CO_2 Phase Diagram



- ***Bottom Line: Dual-purpose infrastructure will need to be designed specifically for LiqH$_2$ and sCO_2.***

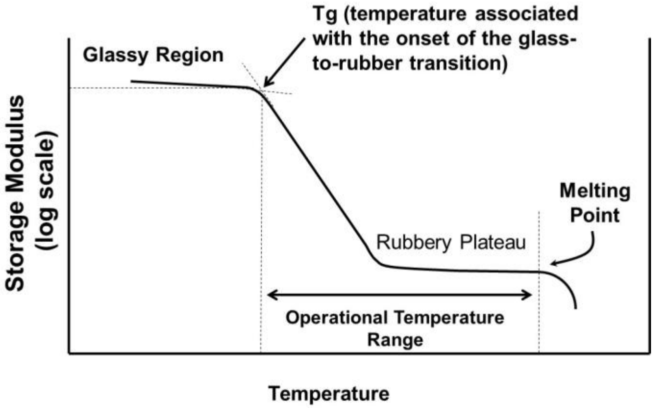
Repurposing ammonia infrastructure for sCO_2 or hydrogen

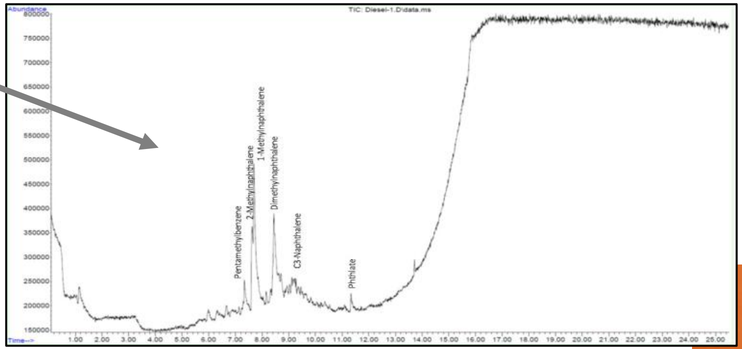
- Ammonia is typically stored/transported as a liquid under pressure to 2bar (29psi) at atmospheric temperature
- Pressures are too low for dense CO_2 and liquid H_2
- Tanks usually composed of carbon and stainless steels. Suitability uncertain for use with hydrogen/NG blends
- Metal components are probably suitable for use with gaseous CO_2, polymer seals need to be evaluated
- Bottom line: more structural operational information needed

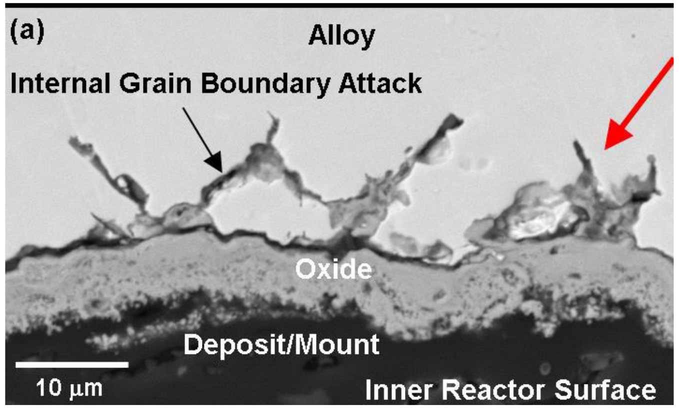


Properties of interest include:

- Polymers
  - mass/volume/hardness
  - Compression set (elastomers only)
  - Spalling/delamination of epoxy coatings
  - DMA
  - GC-MS/FTIR/Raman/X-ray
  - Tensile strength
- Metals
  - Mass loss
  - Corrosion characterization
  - Surface chemistry
  - Yield strength







We recently completed a study examining the materials compatibility of repurposing NG infrastructure for H_2, CO_2 and/or NH_3 transport

- Effort supported by Tim Reinhardt and Evan Frye (Division of Methane Mitigation Technologies)
- Outcomes:
  - Material compatibility assessment based on available literature studies
    - Only study that 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

Subset of tabulated results for polymers (note similar table compiled for metals)

Component	Sub component	Material	Hydrogen Blend	sCO2	Ammonia	Comments
Ball valve	Valve seat	PTFE (Teflon™)	Suitable	Incompatible	Suitable	
	Stem o-ring	NBR	Suitable	Incompatible	Questionable	Depends on the NBR grade
	Stem packing	PTFE (Teflon™)	Suitable	Incompatible	Suitable	
Safety shut valve	Diaphragm	NBR with nylon reinforcement	Suitable	Incompatible	Questionable	Depends on the NBR grade
	Valve heat/seat	Polyurethane	Suitable	Incompatible	Incompatible	
	o-rings	NBR	Suitable	Incompatible	Questionable	
	Seal	Graphite	Suitable	Suitable	Suitable	not a polymer
Appliance regulators	Diaphragm and valve seat	NBR with and without nylon reinforcement	Suitable	Incompatible	Questionable	Depends on the NBR grade
	Valve head	NBR	Suitable	Incompatible	Questionable	Depends on the NBR grade
	Cap and assembly	Molded plastic	Suitable	Suitable	Suitable	Plastic wasn't specified, but should be ok based on survey
	o-rings	NBR	Suitable	Incompatible	Questionable	Depends on the NBR grade
	Valve seat	NBR	Suitable	Incompatible	Questionable	Depends on the NBR grade
		Silicone	Suitable	Suitable	Questionable	Ammonia suitability depends on gas temperature
	Lower diaphragm plate	Polyester	Suitable	Suitable	Suitable	
	Diaphragm	NBR	Suitable	Incompatible	Questionable	Depends on the NBR grade
		Nylon	Suitable	Suitable	Suitable	
	Vent valve/seat	Neoprene	Suitable	Incompatible	Suitable	
		Delrin (acetal)/NBR	Suitable	Incompatible	Questionable	Depends on the NBR grade
	Adjustment Ferrule	Delrin (acetal)	Suitable	Suitable	Suitable	
	Seal cap	Polyethylene	Suitable	Suitable	Suitable	

Key Takeaways

- Existing NG pipelines (excluding compressor stations) likely suitable for low blend levels of hydrogen (in NG), gaseous CO_2, and ammonia
- Existing LNG/LPG infrastructure not currently viable for liquid hydrogen or sCO_2
- Impurities will be important, especially if switching between fluid chemistries
- Current compressor/regulator stations are unsuitable for use with sCO_2 and ammonia
- Need to consider not just material but component performance
- Obtaining precise material information can be challenging

Next Steps

- 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
- Improved understanding of impurities and their contributions to CO_2 corrosion, especially at NG pipeline conditions
- Address key data gaps associated with sCO_2 and polymer compatibility