Pipeline Transport of H2, NH3 and CO2

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Introduction & Scope

As countries all over the world aim for net zero carbon emissions, different energy sources are being evaluated as possible replacements for fossil fuels. One of the biggest challenges with introducing new energy sources into the economy is finding ways to implement that source into the existing infrastructure without large overhead costs. As such, several countries - including the United States - have begun evaluating different commodities including hydrogen gas, ammonia, and carbon dioxide (the latter associated with carbon sequestration): both their compatibility with existing pipeline systems and their validity as safe and profitable sources of energy.

Hydrogen represents a promising low-carbon energy source since the majority is currently gray hydrogen (hydrogen produced using carbon-intensive methods) and already used in multiple necessary industrial processes (CGEP, C, 2023). Methods of producing green (produced using low-carbon electricity electrolysis) and blue (produced using carbon capture and storage) are being improved and are set to produce 97% of hydrogen by 2050, and the overall amount of hydrogen-based fuels produced is predicted to reach 528 megatonnes by 2050 (CGEP, C, 2023). To support this drastic increase, the United States and other countries have considered using both new and existing pipeline systems to transport hydrogen long distance without needing to develop new technology and infrastructure; however, it is necessary to first evaluate the hazards and risks of running hydrogen through these pipelines. Furthermore, it is important to assess the risks and costs of building completely new pipelines and compare that with the hazards of using existing pipelines, and whether new technology must be developed to monitor these pipelines and reduce any risks associated with releases.

Many of the risks associated with transporting hydrogen through pipelines can be tied to the molecular properties of the gas. Firstly, hydrogen is the smallest molecule, so it may be able to pass through pipeline materials used for natural gas and other larger gases. Due to this, estimates suggest that based on the 528 megatonnes goal for hydrogen along with current recorded leak rates, there could be a 5.6% economy wide leak rate (CGEP, C, 2023). Furthermore, pure hydrogen can deteriorate steel pipes, pipe welds, valves, and fittings through embrittlement leading to an increase of slight leaks or full releases during normal operation due to corrosion (CGEP, C, 2023). Another major issue with hydrogen in pipelines and in general is its tendency to combust. In a study done by NASA reviewing 96 hydrogen-related accidents, ignition occurred in all cases with hydrogen released into confined spaces, and in 60% of cases with hydrogen released into open atmosphere (Verfondern, K., et al, 2021). To combat these issues, some projects have attempted to blend hydrogen into existing natural gas pipelines, which would mitigate the risks of using pure hydrogen but has its own drawbacks. For instance, this method would not be viable for a fully net-zero goal, since it still requires the use of methane. Costs aside, this method still would not fully mitigate the issue of hydrogen embrittlement, speeding up the embrittlement by 20% to 50% in the case of existing fractures (CGEP, C, 2023).

Despite the drawbacks, hydrogen blending has been seen to reduce the probability of ignition with blends up to 20% hydrogen, giving at least one benefit of hydrogen as an energy source.

One of the most important parts of reducing climate change is decreasing the amount of carbon dioxide (CO2) in the atmosphere; this can be done utilizing carbon dioxide removal (CDR) from industrial processes. Based on report by the Intergovernmental Panel on Climate Change released in August of 2021, around 5 billion tons of CO2 will need to be removed per year by 2050 (American University Research Center, 2023), meaning a lot of CO2 will be moving through pipelines. This transport may see passage through densely populated areas; as such, it is important that the risks posed by transporting CO2 through pipelines are well-researched and understood.

Anhydrous ammonia is arguably the most dangerous commodity on the list for the scope of this project. It is used as a refrigerant in several industrial and agricultural applications, meaning many ammonia pipelines are present in locations in which heavy machinery is commonly operated. When an ammonia release occurs, it is common for it to incur high financial losses due to both product loss and property damage (EPA, 2001). When an ammonia release occurs in a residential environment, it can lead to severe injuries. The National Institute of Occupational Safety and Health (NIOSH) has set an "Immediately Dangerous to Life and Health level" of 300 ppm for ammonia, as exposure at this level can cause immediate damage to the respiratory system. Additionally, ammonia is a fire and explosion hazard at concentrations between 16 and 25%, which can be reached when anhydrous ammonia mixes with the air at the point of release (EPA, 2001). Overall, the hazards of an ammonia release are quite severe, so it is important to consider how the causes and results of anhydrous ammonia releases differ from the other commodities.

Throughout this report, the team will discuss how the causes of accidental releases differ for the three different commodities (hydrogen, ammonia, CO2), and how the incidents themselves differ among them; for instance, some questions answered in this report include "Do more hydrogen releases ignite compared to other commodity types?" and "Do anhydrous ammonia incidents cause more fatalities than other incidents?" While data regarding liquid natural gas was also reviewed, there were no incidents pertaining to pipeline-specific leaks reported. Because of this, all LNG incidents were excluded from scope of this report. Additionally, this report does not cover how the causes and incidents of pure hydrogen and blended hydrogen releases differ, as there is not enough viable data to make any conclusions to differentiate between the two. Furthermore, this report does not discuss the end uses of any of these commodities, nor the cost of transportation of any of these commodities.

Literature Search

Several projects illustrating the safety of hydrogen blending are or have been active in parts of the United States and Europe. One of these projects, called Hydeploy, powered residential buildings in Winlaton using 20% blended hydrogen for a duration of 11 months. In this time, there were 8 leaks reported throughout the system: 5 were due to leaking joints from loose or corroded bolts (which were not in contact with the hydrogen), one was due to a corroded stand pipe that was replaced under BAU (business as usual) operations, one was due to a leaking plug that was replaced under BAU operations, and one was due to a pipe fracture that was repaired with a 4 inch clamp under BAU operations (Kahlon, 2022). The pipe fracture that occurred took place in October and was attributed to the rapid change of temperatures experienced during the onset of winter. Overall, it was determined that the presence of blended hydrogen gas did not increase the frequency of leaks in the transport pipeline throughout the duration of the trial.

Another project in the UK, called H21, is attempting to collect quantifiable evidence to support that the UK distribution network of 2032 will be completely safe operating on 100% hydrogen. Recently, they completed Phase 1a of testing in a research center at RAF Spadeadam in Cumbria, in which 215 assets were tested with both methane and hydrogen gas to compare their leak rates. Of the 215 assets, 41 of them were found to leak, but only 19 provided sufficient data to compare hydrogen and methane leak rates. These tests showed that assets that were gas tight on methane were also gas tight on hydrogen, and assets that leaked on hydrogen also leaked on methane, including repaired assets. Further, the experimental values found for the ratio of the hydrogen to methane volumetric leak rates varied between 1.1 and 2.2, which was very similar to the modeled values calculated for laminar and turbulent flow, which gave ratios of 1.2 to 2.8. While there was a fairly high leak rate for both methane and hydrogen in iron – around 26-29% of all iron assets leaked – none of the PE assets leaked. Additionally, the four types of joints that were responsible for the most joint-related leaks were screwed, lead yarn, bolted gland, and hook bolts. Finally, all the repairs that were made for methane also worked for hydrogen (H21). Overall, there was not a large difference in the leak rates of methane and hydrogen, and all the repairs made for methane also worked for hydrogen, which shows that with proper safety measures in place 100% hydrogen is possible for the UK distribution network in the future.

One of the most well-known CO2 pipeline releases occurred in Satartia, MI on February 22nd, 2020. This pipeline failure was caused by heavy pressure from soil movement due to heavy rains in the area. As discussed in the introduction, CO2 is normally transported through pipelines in a supercritical phase which vaporizes upon exposure to air and dissipates; however, the unique atmospheric conditions and topographical features of the accident site caused the cloud of vaporized CO2 to dissipate at a much slower rate than anticipated by various models. Local emergency responders were not notified of the rupture and the dangers it incurred, but decided to shut down local highways and evacuate nearby citizens when informed of a "rotten egg smell." As a result of this incident, 200 people were evacuated and 45 were taken to the hospital, but no fatalities occurred (PHMSA, 2022). This event forced PHMSA and other bodies to evaluate the risks associated with transporting hazardous materials through pipelines, especially through densely populated residential areas, incident models for such materials, and emergency procedures post-release. One of the goals of the completed research is to better understand the common causes of these dangerous releases and the negative effects of these incidents.

A noteworthy incident regarding anhydrous ammonia occurred on a Magellan Midstream Partners, LP (Magellan) pipeline near Tekamah, Nebraska on October 17th, 2016. This 8-inch-diameter underground transmission pipeline ruptured and released 2,587 barrels of liquid anhydrous ammonia, which, upon release, vaporized and produced a toxic plume. This incident caused one fatality from respiratory failure due to exposure to the ammonia cloud, and 2 minor injuries. Additionally, 49 people were evacuated and U.S. Highway 75 was closed for several days (NTSB, 2020). This incident illustrates the potential impacts of anhydrous ammonia releases, as this release occurred in a relatively secluded area yet still caused a fatality and had a major impact on the lives of ~50 people. If this incident had occurred in a more densely populated area, there could have been more fatalities and a city-wide evacuation along with collateral damage. As such, it is important to understand the most common causes of anhydrous ammonia releases and what damage these releases can cause.

Methodology

Following unconventional means of obtaining data via online search, the team focused efforts on the Pipeline and Hazardous Materials Safety Administration (PHMSA) database. Through this association, it was possible to efficiently analyze information regarding anhydrous ammonia, carbon dioxide, hydrogen gas, and liquid natural gas incidents and the associated data ranging from time of the incident to specification of the pipeline transporting the fluid. Much of the data was past the scope of the project, such as drug tests of the operators or equipment identification numbers, so the relative information was filtered from the five raw documents provided by PHMSA cited in Appendix A. After reviewing the parameters of focus from this data, the corresponding data was then transferred into new files created by the team, narrowing the upwards of 200 columns down to just 24 (Appendix B). These reduced columns focus solely on the information for further analysis with respect to the scope of the project, and provide valuable insight pertaining to operating locations, conditions, and specifics of each incident that can be readily compared by commodity. Additionally, it is worth noting that during the filtering of raw data, none of the eight liquid natural gas incidents (that were found) were pipeline specific. Instead, all LNG incidents reported by PHMSA correspond to in-facility incidents, where malfunctions in vessels or other equipment led to releases and costly repairs. For this reason, LNG incidents were removed from further analysis during this study.

Having a new, filtered compilation of data provided an adequate space for a multitude of analyses to be conducted. The major component of this step was driven by testing hypotheses and creating various tables, charts, and graphs to determine whether any possible correlations were present among two variables of question. For example, some questions of focus were related to ideas such as "How do the injuries and fatalities compare among the three fuels?” and

"What is the leading cause of incident per commodity pipeline?" These questions, and many more, are explained and answered in explicit detail within further sections of this report.

Results & Analysis

Overall Causes

The largest target from the scope of the project questioned what the biggest concerns for these upcoming commodities are. After creating pie charts depicting the percentages of each of PHMSA's seven categories for hazards to pipelines, there was a repeated leading cause: Material/Weld/Equipment Failure. The depictions of such visuals are provided below.

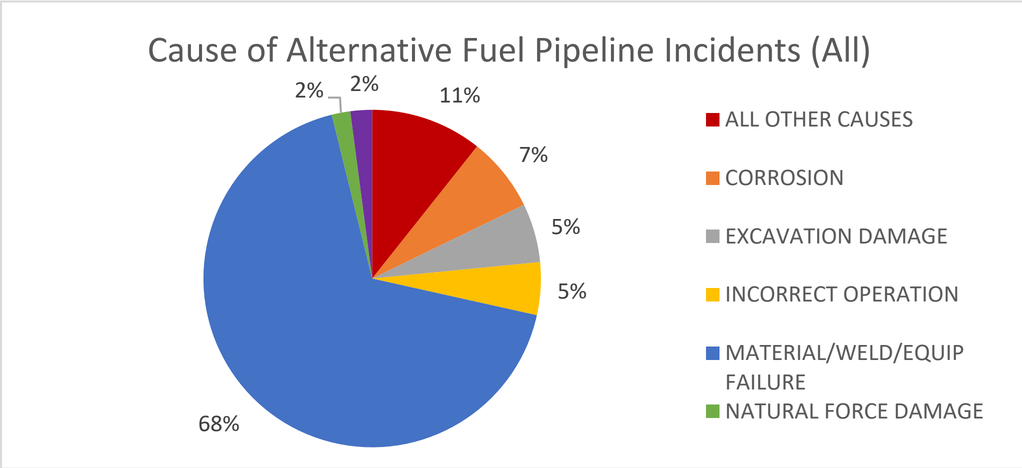

Figure 1.1 Causes for anhydrous ammonia, carbon dioxide, and hydrogen incidents.

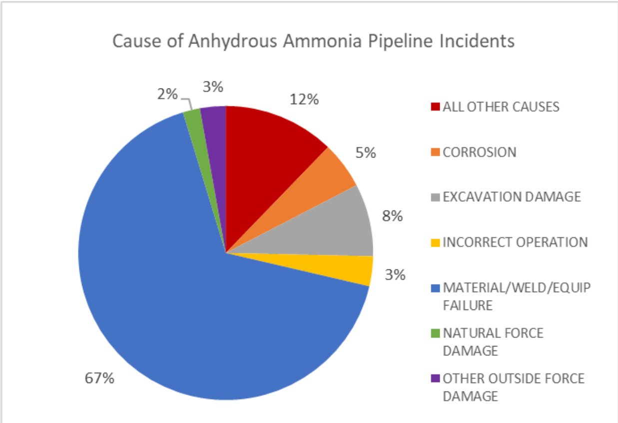

Figure 1.2 Causes for anhydrous ammonia pipeline incidents.

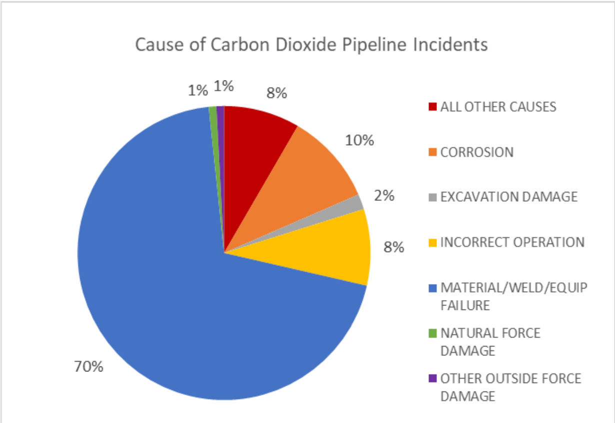

Figure 1.3 Causes for CO2 pipeline incidents.

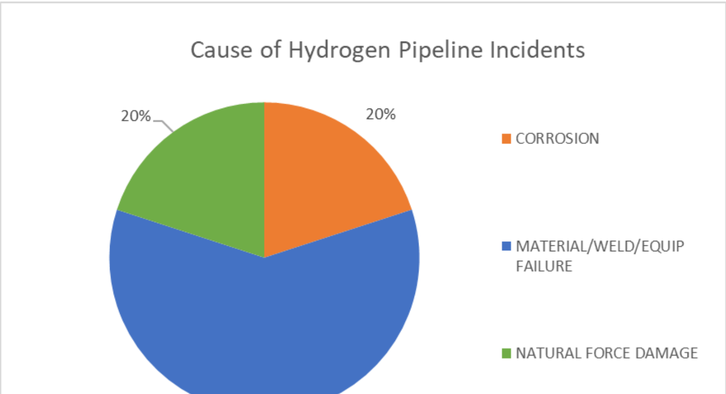

Figure 1.4 Causes for hydrogen pipeline incidents.

Seeing that the leading cause of each commodity's incidents were the same, further interpretation of Material/Weld/Equipment Failure was pursued. Given that PHMSA not only categorizes incidents based on the main cause but also uses "subcauses" within their database, this major category can be broken down to provide a better understanding of the hazards these systems face. For example, Figures 2.1 and 2.2 below depict the leading subcauses for all incidents, as well as per commodity.

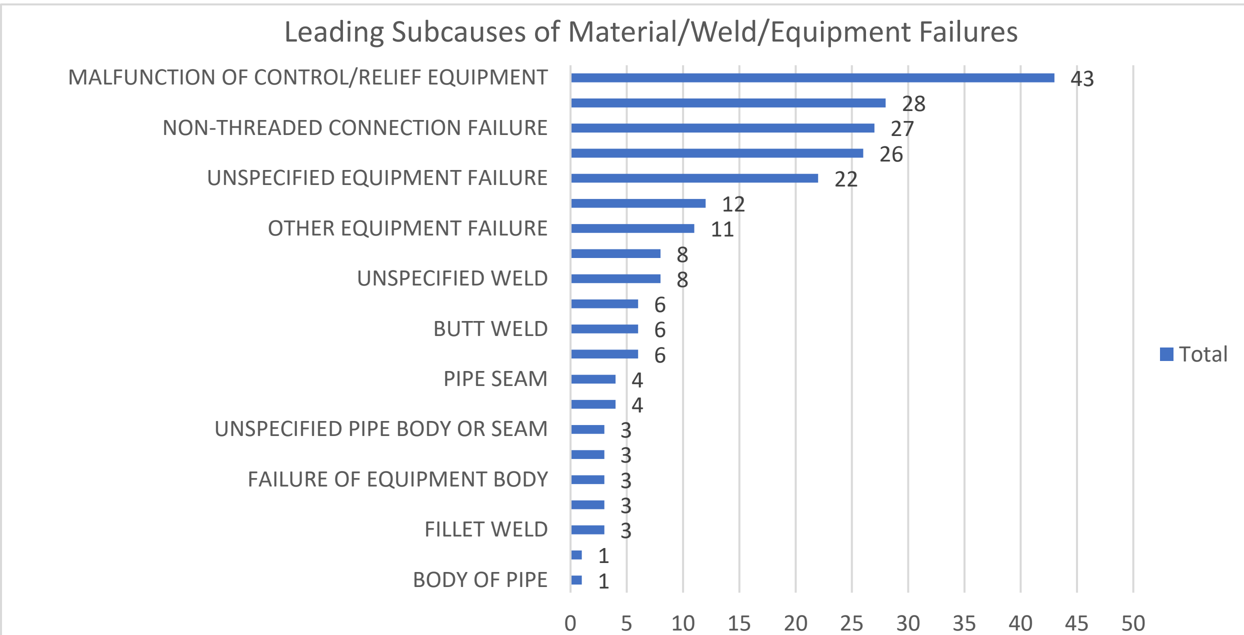

Figure 2.1 Leading subcauses for all alt. fuel pipeline incidents.

MATERIAL/WELD/EQUIP FAILURES	Count of Subcause
ANHYDROUS AMMONIA	
MISCELLANEOUS	23
UNSPECIFIED MATERIAL/WELD FAILURE	22
CONSTRUCTION, INSTALLATION OR FABRICATION-RELATED	21
MALFUNCTION OF CONTROL/RELIEF EQUIPMENT	21
CARBON DIOXIDE	
MALFUNCTION OF CONTROL/RELIEF EQUIPMENT	22
NON-THREADED CONNECTION FAILURE	17
EXTERNAL	10
HYDROGEN GAS	
NON-THREADED CONNECTION FAILURE	1
CONSTRUCTION, INSTALLATION OR FABRICATION-RELATED	1
OTHER EQUIPMENT FAILURE	1
INTERNAL	1
LIGHTNING	1

Figure 2. 2 Leading subcauses of Material/Weld/Equip Failure by commodity.

An overall count of "malfunction of control/relief equipment" in Figure 2.1 far exceeds that of other subcauses; with the uprising of new and untraditional fuels, response and control protocols are just as unfamiliar as the fuels themselves. Ensuring that the operators, communities, and all other stakeholders in the areas of operation are educated on the potential hazards on the transport of alternative fuels will likely reduce this category of incident drastically. For example, one can look at the anhydrous ammonia leak in Riverview, Florida in 2007, where two young teens drilled into an aboveground pipeline, releasing 46 barrels of anhydrous ammonia into the nearby stream and atmosphere. Taking place in a small county, this incident had poor response due to the small fire team tasked with finding a solution. Unfortunately, the fire department not only had minimal training in how to deal with such situations, but also lacked the appropriate level A suits to tackle the situation. Rather than risk the lives of response workers, a decision was made to let the line bleed out and shoot the gas down with water to prevent additional release to the atmosphere. This action instead increased the amount of toxic runoff into a stream.

Consequences

In consideration of how severe these incidents are, graphs were made to compare the three gases with one another in terms of costs, injuries, and fatalities. For the average number of injuries and fatalities, a ratio was determined to provide an accurate representation to one another since all three commodities had a differing count of incident reports. The most notable of this graph is the case of anhydrous ammonia, with 18 injuries and 2 fatalities of the 213 total incidents reported, or a ratio of approximately 8.5 and 1 respectively per 100 incidents. Both carbon dioxide and hydrogen seemed to prevail in this case, with a total count of no injuries nor fatalities per their respective count of incident investigation reports.

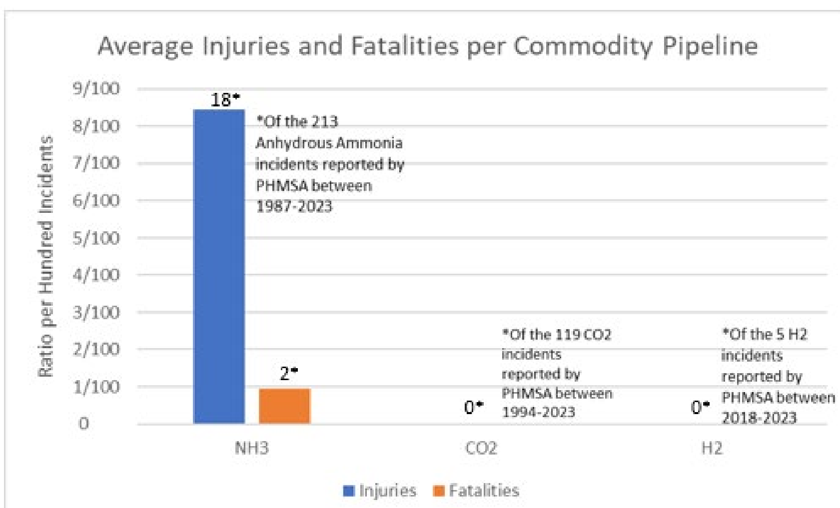

Figure 3.1 Injuries and fatalities by commodity.

The high count of ammonia-related deaths and injuries is most likely due its toxic nature, a characteristic the New York State Department of Health describes as "Exposure to high concentrations of ammonia in air causes immediate burning of the eyes, nose, throat and respiratory tract and can result in blindness, lung damage or death." This sole feature of the fluid can explain the increased health hazards associated with these pipelines. Although not toxic, hydrogen is notorious for its combustibility, which often leads to ignition and explosion. With this fuel being in its infancy, however, there have been no reports of deaths or injuries associated with the five total incidents.

A similar analysis process was followed for that of cost comparison, averaging the total sum of costs per commodity. Prior to taking the averages, it was important that all price data was adjusted to accommodate inflation and other factors. To make this adjustment, PHMSA has included a column in reports named "Total Cost-Current," where all prices have been converted to their current value using the Gross Domestic Product Price Index from 2023 and the year of incident. Figure 3.2 shows results from the average cost per incident, with hydrogen leading at nearly two million dollars per incident. This higher cost is found in hydrogen reports as "Estimated cost of Operator's property damage & repairs," a factor that is significantly higher than that of the other commodities. This is likely due to hydrogen's combustibility, being shown in Figure 3.3 that three of the five incidents reported involved ignition at some time during the release. Additionally, all three of these incidents with ignition also resulted in an explosion, as well. This could explain why hydrogen pipeline incidents are shown to be so much more costly in terms of operator damage, as more damage can be expected from fire or explosion as opposed to the releases in ammonia and carbon dioxide pipelines.

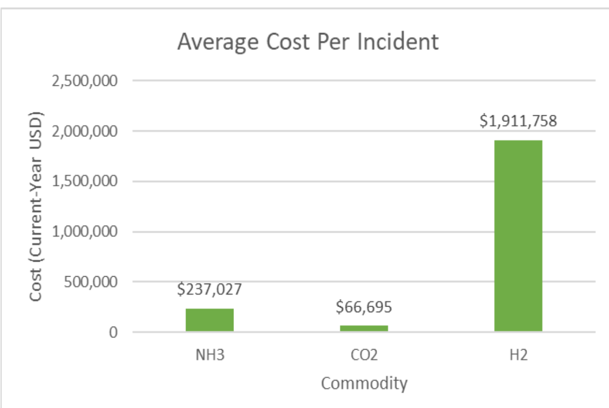

Figure 3.2 Average cost per incident.

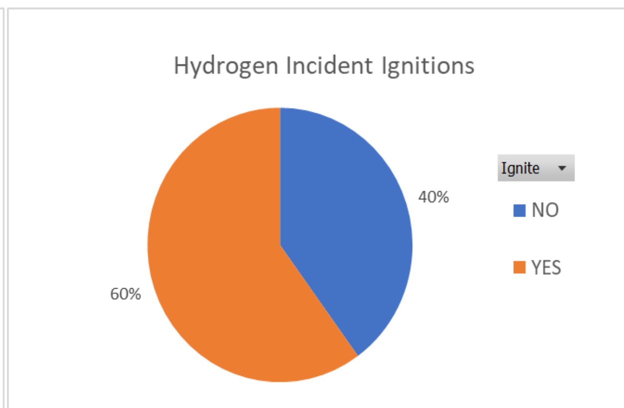

Figure 3.3 Hydrogen incident ignitions.

compared to that of corresponding pipeline operations (Figure 4.2) shows that incidents tend to span all areas where the pipelines are run. Among these incidents, a question arose concerning the count of fatalities and injuries with respect to populated areas. Since many current uses of ammonia pipelines pertain to agricultural use, it was of interest to determine whether injuries and fatalities appeared more likely in densely populated areas. After further comparison with a population density chart from the United States Census Bureau (Figure 4.3), there tends to be no correlation between these two variables with the current data available.

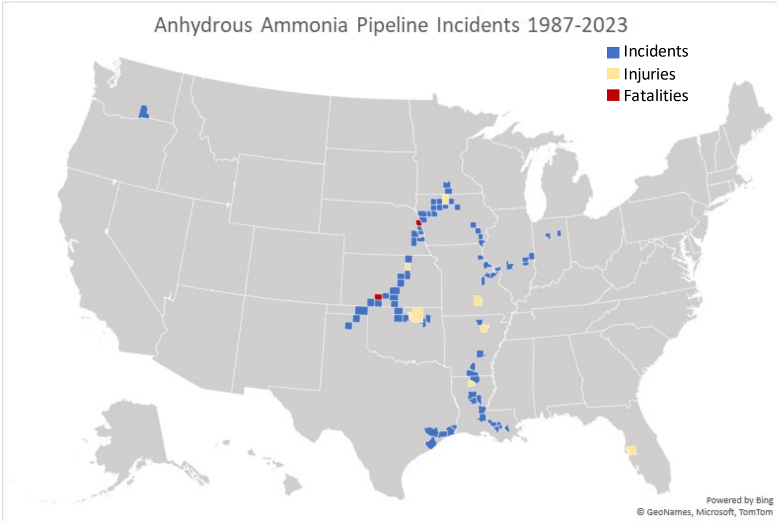

Figure 4.1 Map of anhydrous ammonia pipeline incidents, injuries, and fatalities.

Figure 4.2 US Department of Energy map of anhydrous ammonia pipeline network in 2006.

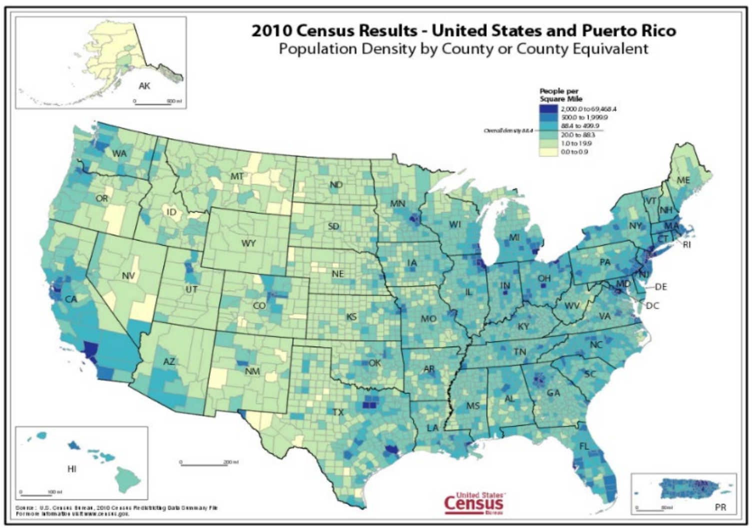

Figure 4.3 US Census Bureau population density map.

Incidents by Mileage

According to the following sources, the pipeline coverage in the United States for the gases studied is as follows:

- Ammonia Energy Association
  - Anhydrous ammonia – ~2,000 miles
- Congressional Research Service
  - Carbon dioxide - ~5,000 miles
- U.S. Department of Energy
  - Hydrogen - ~ 1,600 miles

With this data, the corresponding incidents per mileage, sorted by commodity is as shown:

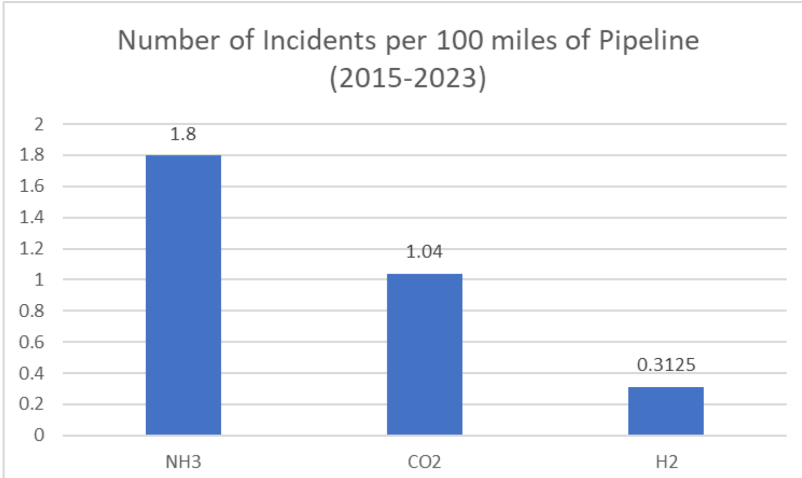

*Figure 5.1 Number of incidents per 100 miles of pipeline.**

*Taken over the years 2015-2023 to account for unequal reporting of H_2 incidents prior to 2015

A surprising result is that anhydrous ammonia incidents tend to be quite more common than that of hydrogen and carbon dioxide pipelines. Looking at the data gathered during research, it is hard to draw just one conclusion explaining this outcome, but some possibilities may include more underlying complications such as the failure to report CO2 incidents since it is considered harmless in comparison to toxic fluids like ammonia. Another suggestion could be that the coverage of the pipeline introduces more factors for failure like corrosion, excavation damage, and other outside force damage, many of which were previously proven to be higher risks for ammonia pipelines in Figures 1.2 and 1.3. This could be the exact case, as from the PHMSA data, 83% of ammonia pipeline incidents occurred in an underground segment of the line, compared to just 29% for CO2 pipelines (Figures 5.2 & 5.3). Furthermore, breaking down the most common causes for above/below ground segments, it is seen that corrosion, natural force damage, and excavation damage are all common causes that do not appear in aboveground scenarios (Figure 5.5); excavation damage specifically having accounted for 8% of all ammonia incidents as opposed to the 2% in carbon dioxide cases. This is a feasible assumption to make, as since most of the ammonia pipeline network is underground, there will be an increased risk of these factors taking place and thus have the tendency to increase the number of incidents.

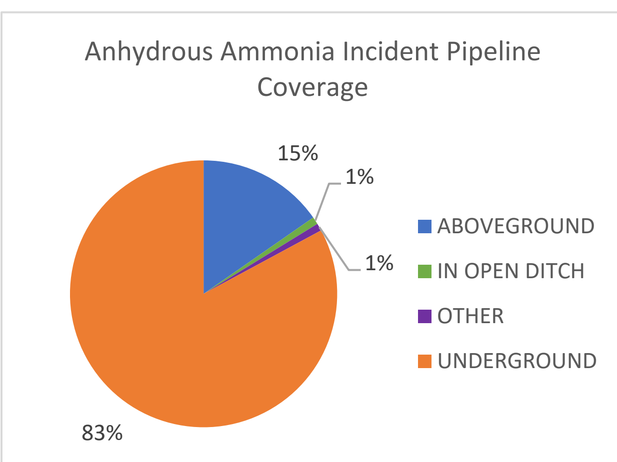

Figure 5.2 Anhydrous ammonia pipeline incident coverage.

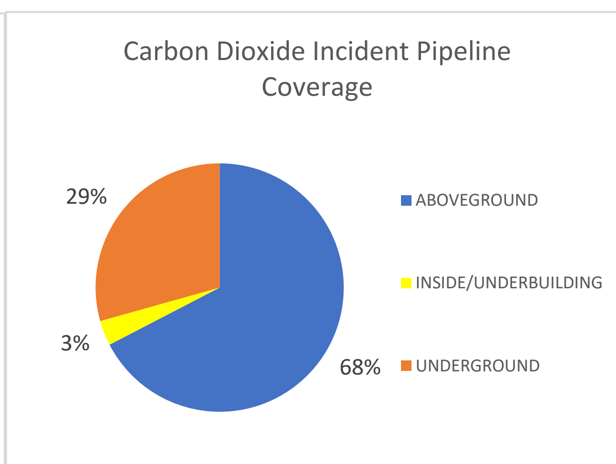

Figure 5.3 Carbon dioxide pipeline incident coverage.

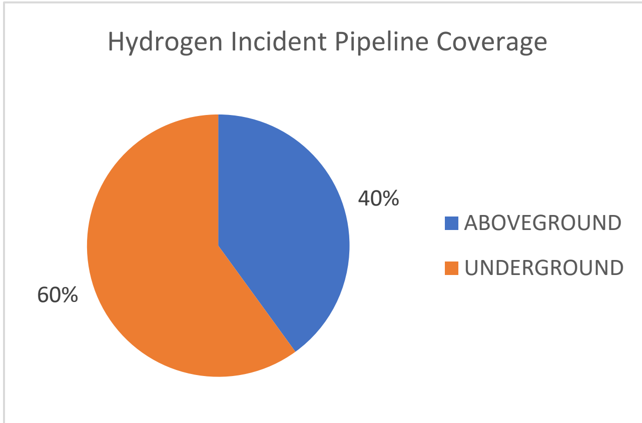

Figure 5.4 Hydrogen pipeline incident coverage.

Pipeline Location	Count of Cause
UNDERGROUND	**122**
MATERIAL/WELD/EQUIP FAILURE	89
CORROSION	18
INCORRECT OPERATION	5
NATURAL FORCE DAMAGE	4
EXCAVATION DAMAGE	3
ALL OTHER CAUSES	2
OTHER OUTSIDE FORCE DAMAGE	1
ABOVEGROUND	**81**
MATERIAL/WELD/EQUIP FAILURE	65
INCORRECT OPERATION	8
OTHER OUTSIDE FORCE DAMAGE	4
ALL OTHER CAUSES	4
INSIDE/UNDERBUILDING	**3**
MATERIAL/WELD/EQUIP FAILURE	3
IN OPEN DITCH	**1**
EXCAVATION DAMAGE	1

Figure 5.5 Incident causes by coverage.

Volume Released

The last analysis examined was the frequency of incidents with respect to the volume released. This proved to be a challenge to appropriately group the incidents, as the volumes ranged from a few hundredths of a barrel to tens of thousands of barrels. The figures below show what was decided to be the best interpretation of the data, grouping the releases in specific intervals, while excluding any counts of "0" listed by the PHMSA reports since it was assumed to be ignored by those filling out the individual reports.

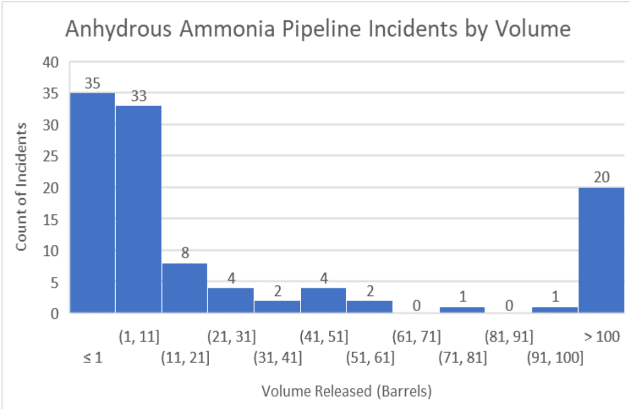

Figure 6.1 Count of NH3 incidents by volume released.

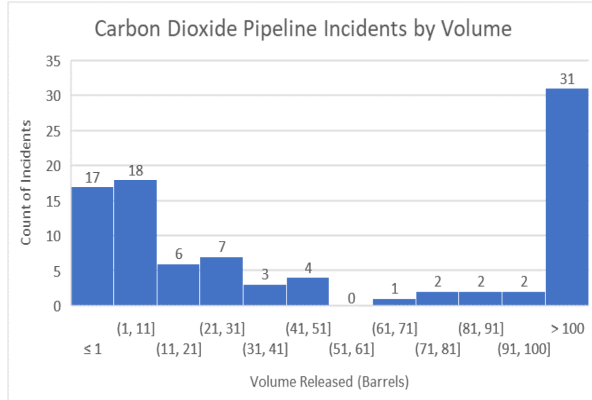

Figure 6.2 Count of CO_2 incidents by volume released.

Figure 2

Commodity	Volume Released (bbls)	Cause
HYDROGEN GAS	1217.72	MATERIAL/WELD/EQUIP FAILURE
HYDROGEN GAS	302.78	CORROSION
HYDROGEN GAS	151.21	MATERIAL/WELD/EQUIP FAILURE
HYDROGEN GAS	146.83	NATURAL FORCE DAMAGE
HYDROGEN GAS	24.22	MATERIAL/WELD/EQUIP FAILURE

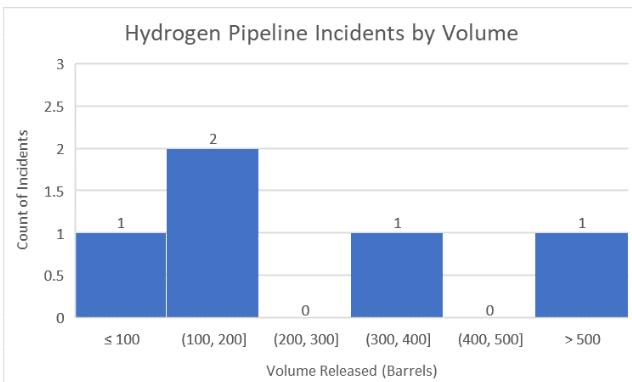

Figure 6.3 Count of H_2 incidents by volume released.

Looking at the individual charts, it immediately becomes visible that many of these incidents result in releases either under ten barrels or over 100. That is apart from hydrogen, however, as its corresponding chart appears to be more evenly distributed with a leading interval of two incidents that released between 100 and 200 barrels. Breaking down these counts even further, it can be decided which causes are more likely to result in higher releases. Figures 6.4, 6.5, and 6.6 below show the top five releases per commodity, as well as the category of cause.

Commodity	Volume Released (bbls)	Cause
CARBON DIOXIDE	41177.00	MATERIAL/WELD/EQUIP FAILURE
CARBON DIOXIDE	24659.00	MATERIAL/WELD/EQUIP FAILURE
CARBON DIOXIDE	24319.00	MATERIAL/WELD/EQUIP FAILURE
CARBON DIOXIDE	9532.00	NATURAL FORCE DAMAGE
CARBON DIOXIDE	7408.00	MATERIAL/WELD/EQUIP FAILURE

Figure 6.4 Top 5 CO_2 releases.

Commodity	Volume Released (bbls)	Cause
ANHYDROUS AMMONIA	5692.00	ALL OTHER CAUSES
ANHYDROUS AMMONIA	4858.00	EXCAVATION DAMAGE
ANHYDROUS AMMONIA	4710.00	EXCAVATION DAMAGE
ANHYDROUS AMMONIA	4513.00	CORROSION
ANHYDROUS AMMONIA	3058.00	EXCAVATION DAMAGE

Figure 6.5 Top 5 NH_3 releases.

Commodity	Volume Released (bbls)	Cause
HYDROGEN GAS	1217.72	MATERIAL/WELD/EQUIP FAILURE
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HYDROGEN GAS	146.83	NATURAL FORCE DAMAGE
HYDROGEN GAS	24.22	MATERIAL/WELD/EQUIP FAILURE

Figure 6.6 Top 5 H_2 releases.

The volumetric sums of each causes' releases were then calculated to reveal the largest factors contributing to the leakage of these commodities (Figures 6.7, 6.8, & 6.9). The biggest surprise among these is that despite only accounting for 8% of all anhydrous ammonia incidents (Figure 1.2), Excavation Damage is the leading cause for the total volume of the gas released. CO2 and H2 incidents are as expected, with Material/Weld/Equipment Failure being the most frequent cause, as well as being the highest contributor to gas released.

Cause of CO2 Incidents	Sum of Volume Released (bbls)
MATERIAL/WELD/EQUIP FAILURE	112602
NATURAL FORCE DAMAGE	9532
ALL OTHER CAUSES	4429
EXCAVATION DAMAGE	4001
CORROSION	3471
OTHER OUTSIDE FORCE DAMAGE	1208
INCORRECT OPERATION	483

Figure 6.7 Volume of CO2 released by cause.

Cause of NH3 Incidents	Sum of Volume Released (bbls)
EXCAVATION DAMAGE	18416
ALL OTHER CAUSES	7295
CORROSION	5907
MATERIAL/WELD/EQUIP FAILURE	5142
NATURAL FORCE DAMAGE	2522
OTHER OUTSIDE FORCE DAMAGE	441
INCORRECT OPERATION	89

Figure 6.8 Volume of NH3 released by cause.

Cause of H2 Incidents	Sum of Volume Released (bbls)
MATERIAL/WELD/EQUIP FAILURE	1393
CORROSION	303
NATURAL FORCE DAMAGE	147

Figure 6.9 Volume of H2 released by cause.

Conclusion & Next Steps

While it is evident that more research and test cases should be conducted to fully determine the differences in the amount/cause of accidental releases as a result of the type of gas used, there are some conclusions and recommendations that can be generated from this data. First, it is important to recognize that results drawn from this data could be related to the increased failure to report certain types of incidents when compared to others; for instance, failures to report CO2 incidents may be more common than failure to report anhydrous ammonia reports since the latter is normally much more dangerous and destructive. Additionally, since hydrogen often tends to explode when released – therefore causing a disproportional increase in financial loss due to property damage – more hydrogen incidents may be reported due to this increased damage and financial loss when compared to the other commodities, which may not cause as much damage when released in small quantities. Furthermore, PHMSA reports - which were the team's main way of gathering evidence - are filled out by the user, not by a standardized source. It is possible that this would lead to inconsistencies in the standards of the reported data, as some users may be more thorough than others while filling out incident reports. Finally, the incidents per mileage data is also limited based on which incidents were reported and which were not: it is possible that there were small incidents that were deemed inconsequential and therefore left unreported, meaning the team's calculated values for incidents per 100 miles of pipeline were skewed. As such, it is important to remember this research is limited based on what was reported; any incidents that were unreported could not contribute any data.

One method that could build on this research is to compare the data analyzed in this report to the data found in other sources. The team acquired most of the data analyzed in this report from PHMSA, so comparing this data to the data found in other databases may help reduce any inconsistencies caused by the PHMSA reporting system. Overall, this will build on the number of reports analyzed and help reduce any errors caused by inconsistent reporting.

Going forward, the team recommends that to build knowledge and develop necessary, hazard-reducing technologies, more research should be conducted in controlled environments to determine the different characteristics of the causes and results of releases of the different commodities. The team found that the most common cause of pipeline releases for all commodities was material/weld/equipment failure, which makes sense, since the lack of experience regarding these commodities leads to improper handling of pipelines and operational repairs. As such, this cause should be researched further. For example, some research-defining questions that can be asked include "Does this pipeline material lead to more hydrogen releases due to material failure?" and "Does pipeline material lead to more corrosion from CO2?" While the other general causes of pipeline failure did not have as many releases as material failure, these causes are also important to study and should be researched as well to limit more incidents in the future.

Moving forward, research into different technologies to mitigate the effects of these releases will be very beneficial since it would allow for further development of pipeline infrastructure, even through more densely populated areas. It is evident that more research is needed concerning these topics moving forward, especially since more operational pipelines for these commodities are necessary to reach the carbon-neutral goals that have been set for 2050.

Appendix

A. Raw Data

- Gas Transmission, Gas Gathering, and Underground Natural Gas Storage Incident Reports for 2010 - present (PHMSA Form 7100.2 Rev. 1-2020)
- Hazardous Liquid Pipeline Accident Reports for 1986 - 2001 (PHMSA Form 7000-1 Rev.04-85)
- Hazardous Liquid Pipeline Accident Reports for 2002 - 2009 (PHMSA Form 7000-1 Rev.04-85)
- Hazardous Liquid Pipeline Accident Reports for 2010 - present (PHMSA Form 7000-1 Rev. 3-2021)
- Liquefied Natural Gas (LNG) Facilities Incidents for 2011 - present (PHMSA Form 7100.3 Rev. 9-2019)

B. Formatted Data

- Incident Summary and Analysis

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