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Likelihood, causes, and consequences of focused leakage and rupture of U.S. natural gas transmission pipelines

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ABSTRACT

The safety of pipelines that transport energy (particularly natural gas transmission pipelines) has become an important and controversial issue with the general public. This study provides strong evidence that the US transmission pipeline network is safer than many believe. Published estimates of risk of pipeline failure are typically in the range 1.2×10^{-4} to 6.1×10^{-4} per km yr. Risk of pipeline failure differs significantly with diameter, with fatality rates of 4.6×10^{-6} per km yr for larger pipelines and 2.4×10^{-6} per km yr for smaller transmission pipelines. The average injury rate was 1.9×10^{-5} per km yr for smaller pipelines, compared to 5.9×10^{-6} per km yr for larger transmission pipelines. The failure rate for large diameter transmission pipelines is larger, the older the pipeline segment. The joint impact of pipeline diameter and wall thickness on failure rate reveals that increased wall thickness is effective in mitigating risks. Overall, natural gas transmission pipelines have significantly lower fatality rates than do truck or railway transport of hazardous materials. For larger transmission pipelines, the estimated rates for serious injuries (3.0×10^{-6} per km yr) and fatalities (6.3×10^{-7} per km yr) for the public, are at a level generally considered acceptable by most countries.

1. Introduction

The International Energy Agency (IEA) (International Energy Agency, 2011) has recently suggested that globally we may be "entering a golden age of gas". By that the agency meant that natural gas was becoming a significant component of the world's energy mix. This has widespread implications for greenhouse gases, the petrochemical industry and a large range of other energy issues. However the IEA cautions that "there will always be uncertainties" and that there could be obstacles to increased unconventional gas production. One such uncertainty is the ability in the future to permit and construct natural gas transmission pipelines. A report by a US national Academy of Sciences investigation concluded that "the consequences of incidents that involve large-diameter, high-pressure transmission pipelines can be significant for public safety and environment" (U.S. National Academies, 2004). The current situation with the Keystone XL oil pipeline in the US demonstrates that concerns over safety and the risks of pipeline accidents can have major impacts on energy issues. There is an imperative that accurate, unbiased evaluations of pipeline safety be published.

Natural gas has become one of the most important energy sources for the United States. Natural gas production increased from 18,593,792 million cubic feet (MMcf) in 1990 to 22,381,873 MMcf in 2010 (U.S. Energy Information Administration). Over the last 60 + years, a large pipeline network has been constructed to transport natural gas. By 2012 there were 2,035,253 mi (3,274,722 km) of gas distribution pipeline and 317,516 mi (510,883 km) of natural gas transmission pipeline. Future expansion of the natural gas transmission pipeline network in the United States, as a result of the rapid development of shale-gas reserves, is likely.

Understanding and, if possible, improving the safety of natural gas pipelines is an important issue. The U.S. Department of Transportation (DOT) has noted that half of the existing U.S. pipeline network was constructed in the 1950's and 1960's in response to the large increase in energy demand of the U.S. economy after the end of World War II. The potential impact of an aging pipeline network is an ongoing concern.

There are three types of natural gas pipelines in the United States. *Gathering pipelines* collect the natural gas produced from wells and transport it to processing facilities or connect to transmission pipelines. Gathering pipelines typically range in diameter

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from 2 to 12 inches (5.08–30.48 cm) and operate at pressures of 800 pounds per square inch (psi) (~5516 kPa). A small percentage of gathering pipelines, constructed over the last decade and associated with unconventional gas development in the US, have diameters and operating pressures of the same magnitude as medium-large transmission pipelines (Wang & Duncan, 2014).

Transmission pipelines take natural gas from processing plants near the fields to domestic markets (major cities) and sites of large-volume users (factory complexes and gas-fueled power plants). Transmission pipelines have the largest diameters (12–42 inches, 30.48–106.7 cm) and operate at pressures up to 1440 psi (9653 kPa). More than 12% of the transmission pipelines in the United States were constructed before the 1950's. More than 200,000 mi (321,868 km) of gas gathering and transmission pipelines exist in the United States. *Distribution pipelines* deliver natural gas to residential, industrial, and commercial end users. These pipelines are typically smaller in diameter (1–2 inches, 2.54–5.08 cm) and have lower pressures (<100 psi, 689.5 kPa), and they are often older than the other classes of pipelines.

The present study focused on transmission pipelines, which, as they have larger diameters and carry gas under high-pressure present the largest potential hazard. These lines follow routes that traverse a variety of terrains and have to cross obstacles such as highways, railways, other pipelines, and rivers. In some cases urbanization has encroached on pipelines originally routed through rural areas. All of these present the potential for hazards of various types. In general, transmission pipelines have a lower risk of significant incidents than distribution pipelines because transmission pipelines typically traverse terrains with lower population density and are subject to less chance of third-party interference.

Duncan and Wang (2014) concluded that previous estimates of individual risk associated with natural gas pipelines being used in quantitative risk analyses, ranged from 1.2×10^{-4} to 6.1×10^{-4} per km yr. We chose to normalize to a 1 kilometer metric as the hazard distance associated with the pipeline ranges from <20 m for a small distribution pipeline at lower pressure, up to >1 km for a larger transmission pipeline at higher pressure (Vianello & Maschio, 2011). Although a few unpublished reports have used the DOT natural gas pipeline data over the last few decades few if any published analyses of these data are available. Papadakis (Papadakis, 1999) estimated "the annual casualties rates per failure in US gas transmission" in the period 1984–1996 as relatively constant, approximately 3×10^{-5} per km yr (of which he noted, fatalities accounted for only 15%). Guijt (2004) in an article in the Oil and Gas Journal has estimated from DOT data that the risk of an injury being caused by natural gas pipelines in the US is 2.5×10^{-5} km yr and the risk for fatalities is 0.7×10^{-5} km yr. Unfortunately Guijt (2004) did not differentiate between transmission, distribution and gathering pipelines.

This study does not attempt to assess issues such as estimation of societal risks or strategies for routing pipelines to minimize risks. Rather, our aim is to develop a robust understanding of the likelihood of failure of natural gas pipelines and to improve understanding of the factors causing these failures. Our study of natural gas pipeline risks is based on analysis of a relatively new incident database made available by the U.S. DOT. The objectives of this paper are to (1) better understand the probability of failure for natural gas transmission pipelines using incident data collected in the United States from 1990 through 2009; (2) examine the relative importance of the factors that cause pipeline failure; and (3) assess the consequences of pipeline failure with respect to property damage, fatality/injury rate, and volume of natural gas released. This paper is organized as follows. Background information and motivation for this study are provided in this section, followed by Section 2, a description of the data set and our methodology. In Section 3 we present an analysis of failure rates that is based on the data set of natural gas pipeline incidents in the United States and discuss the relative role of factors resulting in pipeline leakage and rupture. In Section 4, we compare results of our study with results of previous assessments in reports and published literature. Major findings from this study are listed in Section 5.

2. Data set and methodology

2.1. Data set

The Pipeline and Hazardous Materials Safety Administration (PHMSA) of the U.S. DOT maintains a database of natural gas gathering and transmission pipeline incidents since 1990 (U.S. Department of Transportation), as well as related pipeline statistics. The incident data collecting form was revised in 2002 to gather more detailed information about incidents. The data sets for the period from 1990 through 2002 (PHMSA 90/02) and for the period from 2002 through 2009 (PHMSA 02/09) include the location, determined cause, duration, and consequences (economic loss and deaths/injuries) of each incident, along with the diameter and thickness of the pipeline involved.

The PHMSA 02/09 includes more specific information on the nature of the incidents, e.g., leakage type (pinhole, puncture, or connection failure), and rupture type (longitudinal crack or circumferential separation), whether a fire or explosion occurred, and estimated property damage. The PHMSA classifies all pipeline incidents as significant (defined as those incidents that caused more than $50,000 in damage or led to fatality or injury requiring in-patient hospitalization) and non-significant.

This database is of considerable interest for risk studies because it makes available a rich set of information on pipeline incidents. However it does have limitations. As we divide the data set into small subsamples, to look at say the causes of pipeline rupture in transmission lines greater than 20 inches in diameter, the sample sizes can become small. We have preferred this approach over averaging disparate data to get larger sample sizes on less meaningful samples. The best approach statistical analysis of these types of data is not obvious and will be the subject of future research.

2.2. Nature and consequences of pipeline incidents

Depending on the nature of the failure mode of the pipeline, specific incidents are classified into categories: leaks, ruptures, or system-component failures. A leak is defined as a failure of the body of the pipeline, in the form of pinholes or punctures. A rupture is a longitude or circumferential crack that results in a gas leak. System-component failures include malfunction of valves, failure of mechanical joints, breaks in fittings, or flaws in compressors.

Following investigations, failures of natural gas pipelines have been attributed in the PHMSA database to a number of causes, such as (1) internal corrosion, (2) external corrosion, (3) outside forces, or (4) defects in construction or materials. Internal corrosion occurs as a result of acid forming in the presence of water. Potential acid-forming constituents in pipelines include CO_2, SO_2, and NO_2. For natural gas pipelines, CO_2 is by far the most likely cause of acid formation. Internal corrosion rate is affected by many factors, such as temperature, flow, and type of steel. Nešić, (2007) provided a comprehensive review of the nature and mechanisms of internal corrosion in oil and gas pipelines. External corrosion acts on the outside of buried gas pipelines and reduces their structural integrity (Jack & Wilmott, 1996). A number of approaches have been taken to mitigate external corrosion, including various pipeline coatings and cathodic protection (Winning, Taylor, & Ronceray, 2010). Outside forces include accidental excavation or natural