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Economic impact of applying high strength steels in hydrogen gas pipelines

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ABSTRACT

Steel pipelines will likely be employed extensively to transport gaseous hydrogen in support of a future clean energy economy. To date, a hydrogen-specific cost analysis of pipeline installation has not been produced. This paper performs several cost analyses in order to quantify cost differentials associated with hydrogen pipeline installation relative to (a) natural gas pipeline installation, (b) use of different pipe diameters and operating pressures, (c) use of X70 pipeline steel, and (d) use of X70 pipeline steel given a potential change in governing design code. The analysis concluded that there is a sizeable cost increase between natural gas and hydrogen pipeline installation (as much as 68%, depending upon conditions). Furthermore, the analysis concludes that considerable cost savings can be realized if the hydrogen pipeline design/engineering code were modified to allow the use of X70 steel without penalty. Cost saving on the order of 32% may be realized, relative to use of X52 designed to the current code.

Introduction

The use of hydrogen for energy storage is one of many concepts being developed to increase usage of renewable energy sources. Hydrogen is a clean-burning fuel that can be used as a replacement for fossil fuels in internal combustion engines or in electrochemical fuel cells used to produce electricity. In both cases, the resultant byproduct is water vapor. Several major automakers, including Honda, Toyota, and Hyundai, are committed to producing commercial quantities of fuel cell vehicles in the 2015–2017 timeframe [1]. Although initially the hydrogen infrastructure will likely depend on over the road transportation in tank cars or tube trailers, ultimately the ability to move large quantities of hydrogen economically will depend on availability of pipelines. Pipelines are the most economical choice for transporting large quantities of fuels for long distances, with the most relevant example being that of natural gas. Pipeline delivery of hydrogen fuel is especially cost-effective in high-demand, densely populated markets [2]. The U.S. contains nearly 300,000 miles of interstate and intrastate transmission pipelines [3]. In contrast, the nation's network of hydrogen pipelines totals only 1500 miles [4].

Unlike natural gas, hydrogen is known to have a detrimental effect on the mechanical integrity of steel. When hydrogen is compressed within a pipeline, some of it adsorbs and subsequently absorbs into the wall of the pipe, which causes reductions in ductility and toughness. For this reason,

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the codes used for engineering of hydrogen pipelines have higher safety margins than those used for natural gas pipelines. While these margins have given hydrogen pipelines an excellent safety record, they also increase their cost. Although the cost of producing and distributing hydrogen is being reduced, more work is needed to make hydrogen cost-competitive with other fuels. This includes reducing the cost of pipeline transmission and distribution. For this reason, extensive ongoing research has been focused on developing a deeper understanding of hydrogen effects in steel, so that safety margins can be optimized and pipeline costs reduced without compromising safety and/or performance.

This paper focuses on the costs associated with hydrogen pipeline installation. A cursory review of the deleterious effects that hydrogen has upon steel is presented for background and analysis are presented to provide relative cost differential for hydrogen-service pipe with respect to natural gas-service pipe. Based on this knowledge we will present plausible opportunities for changes to engineering methods that could reduce costs without compromising safety. We will also identify areas where work is still needed to make the vision of lower cost pipelines a reality.

Effect of hydrogen on steel properties relevant to pipeline engineering

The embrittling effect of hydrogen on steel has been well known for decades, and mitigating this effect is important in many structural applications. As is true in most applications, the loading and environmental characteristics dictate the materials property requirements. Sufficient yield strength is key to ensure that the pipeline can withstand stresses caused by internal pressure. Fracture mechanics methods are used for pipeline design and structural integrity monitoring using parameters such as fracture toughness. Fracture toughness also determines a pipeline's resistance to third party damage, such as from impact from digging equipment. Fatigue crack growth resistance is especially important to gas pipelines. In addition to transporting gas, pipelines can be used as part of the storage strategy. By increasing and decreasing the pipeline pressure, gas can be stored and released as part of normal operation. In practice these pressurizing/depressurizing cycles take place once or twice a day, and the minimum pressure is generally 75–80% of the maximum pressure. In fatigue terminology, this is an application with a high load ratio value (R value)[1] and low frequency. The low frequency can exacerbate hydrogen effects, since the growing crack, when held open at the peak of the load cycle, provides an easy path for hydrogen absorption. Hydrogen can also have a deleterious effect on fatigue crack initiation and high cycle fatigue life, commonly characterized by stress-life (Wohler or S–N) curves [5]. However this duty cycle is more common in vehicle applications as opposed to pipeline service. Thus development of S–N data has not been a focus for pipeline applications to date.

In addition to these requirements for the base metal, steel alloys for pipelines must have adequate weldability to ensure that weld beads and accompanying heat affected zones have the correct levels of strength and toughness for the application. Many modern pipeline steels are manufactured using thermomechanical processing schemes such as controlled rolling, recrystallization controlled rolling and post rolling accelerated water cooling practices. These processes enable development of steels with high strength, but much lower alloy contents, resulting in lower carbon equivalents and resulting in improved weldability [6]. The properties of welds are also important, as the microstructures of these materials are different than the base metal by virtue of the thermal cycling (and the melting/resolidification) they endure during the welding process. In addition, the violent nature of the weld process increases the likelihood of embedded defects such as inclusions or porosity. These defects can limit the performance of a welded pipe, and their impact on mechanical properties must be comprehended to ensure safe pipeline operation. Though outside of the scope of this paper, longitudinal welds, circumferential welds, and their respective heat-effected zones are also impacted adversely by gaseous hydrogen. These effects are not yet well understood and work is progressing at both NIST and Sandia National Laboratories to elucidate these effects. Corrosion resistance is also an important characteristic for pipeline service, but this topic is outside the scope of this paper.

[1] R value is the ratio of the minimum to the maximum load.

Cost factors in pipeline engineering

When pipeline cost estimates are needed for studying the cost of producing and delivering hydrogen, cost studies for natural gas pipelines are used as a starting point, based on data compiled by the Oil and Gas Journal. Construction costs are broken into four categories [7]: Labor, Materials, Right of Way and Miscellaneous. Table 1 shows the average breakdown.

As pipeline costs are generally quoted in dollars per unit length (e.g. $/mile), material costs scale with both the diameter of the pipeline and the operating pressure. Labor costs are also impacted by material costs, especially by thickness, since thicker wall pipelines require more welding and heavier pipes may require more robust installation equipment. Right of way and miscellaneous costs are generally independent of material. However, right of way costs can vary by a factor of 7 based on where the pipeline is being installed [8].

Changing the fuel being transmitted from natural gas to hydrogen affects the labor and materials cost components; however, a thorough treatment of these effects does not exist. The U. S. Department of Energy's Hydrogen and Fuel Cell Program has been working towards lowering the cost of hydrogen production, storage and distribution, and as part of their work have developed technoeconomic models of the

Table 1 – Cost contributions for natural gas pipeline construction (from reference [7]).

Labor	45%
Materials	26%
Right of way	22%
Miscellaneous	7%