Technical Study of Feasibility of Using City Gas Pipelines for Hydrogen Supply Network

- Contributions to Reducing Environmental Impact with Hydrogen as the Ultimate Clean Energy –

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1. Introduction

After the massive earthquake that hit the Northeastern region of Japan on Mar 11, 2011, all nuclear power plants in Japan were halted. As a result, energy supply pathways to realize a low carbon society are dramatically changing. On April 2014, a Cabinet Decision was made to adopt the New Strategic Energy Plan in which, 'Future of the Secondary Energy Structure' was presented. A section of this is dedicated to 'Acceleration of Steps Toward Realization of a *Hydrogen Society*' and says 'As for the secondary energy in the future, it is expected that hydrogen will play an essential role, as well as electricity and heat.' It further describes the plan to deploy hydrogen stations for fuel cell vehicles, starting from 2015. Since about 20% of CO_2 emission in Japan comes from the transportation sector, this is an important step for reducing CO_2 emission. To drive down the construction cost of hydrogen stations, various deregulations are on the way, and hydrogen is becoming a significant element in Japanese society.

The Japan Gas Association believes it is very important to be well prepared for the forthcoming hydrogen society. We have been a part of an investigation project 'Study on Hydrogen Supplying Network Safety Engineering,' to systematically study how we can secure and maintain a hydrogen delivery network. This project was commissioned by the Ministry of Economy, Trade and Industry (METI) in 2012. In this paper, we will report the progress made in FY2013. (FY ending March 31, 2014)

2. Project Structure

The project consists of five components; 1) Comprehensive Study, 2) Research of hydrogen-substitution behavior, 3) Analysis of gas pressure inside the hydrogen pipeline, 4) Safety evaluation of installation/construction of gas supply equipment, and 5) Research on impact of odorant additive to hydrogen embrittlement of metallic material of the pipeline.

The project is driven by a steering committee, which is a team of experts in the related fields, and respective Working Groups (WG) consisting of gas companies, research institutes, and other companies from related industry. All were responsible for planning the contents of researches, execution of the plans, and review of the results (See Fig.1).

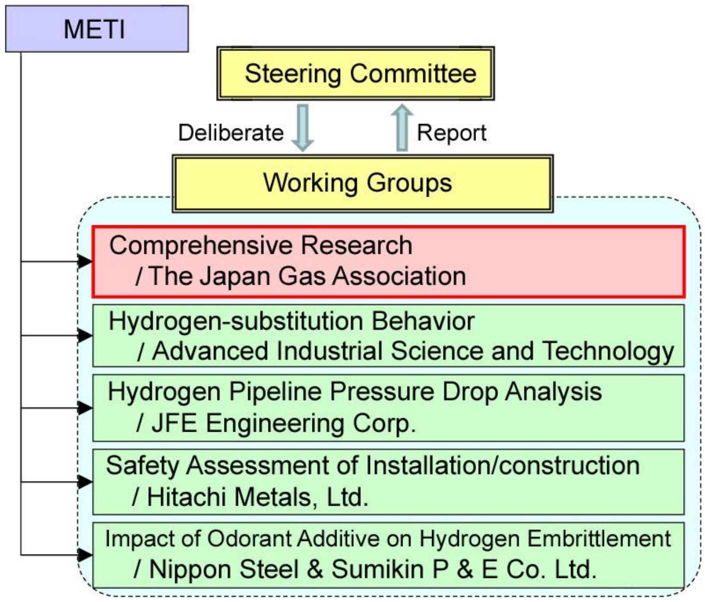


Fig.1 FY2013 Project Organization Chart

3. Summary and Results of Each Research

(1) Research of Hydrogen-substitution Behavior

a) Scope of the Study

After installing a new pipeline for hydrogen delivery, the primary concern is the mixture of air and hydrogen. When the rate of hydrogen is 4 - 75%, any ignition source near-by can trigger a disaster. When substituting air with hydrogen, the standard procedure to prevent hydrogen from igniting is to fully fill the pipeline with inert gas and purge out all the occupying air. However, from an economic standpoint, we looked into what amount of inert gas is actually required to prevent hydrogen from mixing with air.

b) Summary of the Study

As shown in Fig.2, we experimented a method to introduce hydrogen without letting it mix with air by squeezing in a nitrogen layer in between air and hydrogen. We first injected nitrogen, and then hydrogen following that. Nitrogen-hydrogen mixed layer ℓ1 has a nitrogen concentration of 2% - 98%. The conditions of the experiment are shown in Table 1.

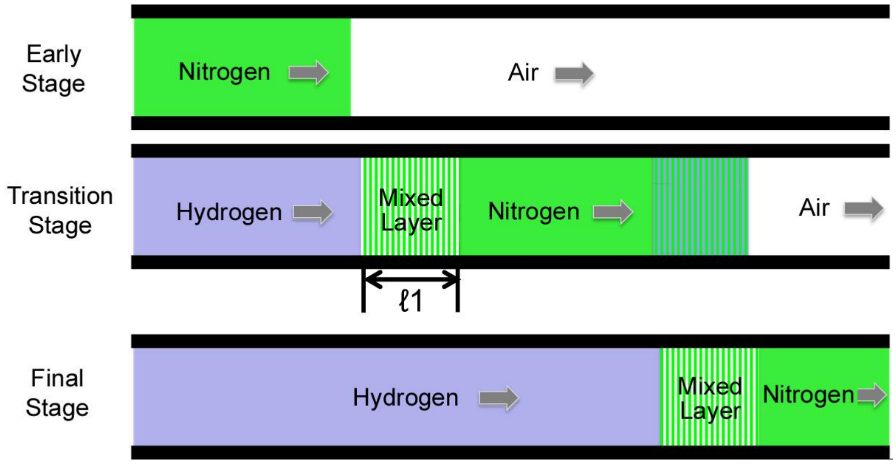


Fig.2 Progression of Gas Mixture in the Pipeline

Table 1 Experiment Condition

Item	Conditions
Type of pipe (Outer diameter: mm)	25A (34.0), 50A (60.5), 100A (114.3), and 150A (165.2)
Hydrogen flow velocity	3 levels for each diameter
Initial Nitrogen flow rate	2-3 levels for each flow velocity

c) Result of the Study

Fig.3 shows the time response of oxygen, nitrogen, and hydrogen concentrations at a certain cross section of the pipeline. It can be seen that the substitution proceeded without all the gas getting completely mixed. It was assumed that diffusion was most incident at the Nitrogen-hydrogen mixed layer, so we've done analytical study on the length of Nitrogen-hydrogen mixed layer ($\ell 1$), and obtained dimensionless expressions using the Reynolds Number (*Re*). We discovered that when the length of the mixed layer ($\ell 1$) meets a certain condition, it is unnecessary to completely fill the conduit with inert gas (nitrogen, in this case).

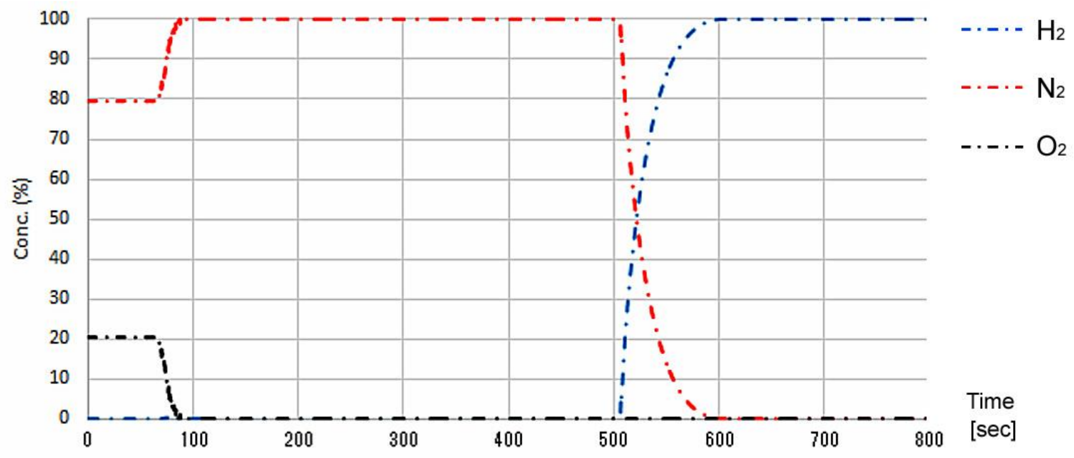


Fig.3 Measured Concentration Progression on Each Gas in Pipe

Table 2　Dimensionless Expression with Reynolds Number

$L \leqq 20$	$20 < L \leqq 80$
$\ell 1 = (0.0227 Re H_2 + 202) \cdot d$	$\ell 1 = (0.0833 Re H_2 + 328) \cdot d$

Note: Only when $ReH_2 \leqq 2{,}000$　(Nitrogen $Re \leqq 14{,}000$)

(L: Total pipe length, $\ell 1$: N_2-H_2 mixed layer length, d: Pipe diameter)

2) Analysis of Gas Pressure Inside the Hydrogen Pipeline

a) Scope of the Study

The purpose of this study is to find out whether a set of reduced equations similar to what is used to analyze city gas flow can be derived for hydrogen pressure drop. For this, we examined whether the data collected were consistent with generic flow analysis tools such as Colebrook equation. We also looked into the pressure drop behavior at the fittings like elbow joints and T-joints. Conventional method for this kind of analysis is Equivalent Method (L_e/D), in which we approximate fittings into straight pipe equivalents. We investigated whether this could be applied for hydrogen as well.

b) Summary of the Study

We built a test bench as shown in Fig.4 and pressure drop in low-medium pressure (< 1MPa) range was measured for various pipe diameters (40A – 100A). Then we developed a set of pipeline pressure analysis equations, based on some theoretical formulas.

We also needed to establish a method to analyze pressure drop at fitting parts within a mid-low pressure hydrogen pipeline. For this purpose, we constructed a section in the test bench for measuring pressure drop at fittings. The fittings used in this research were elbow joints, and T-joints. As shown in Fig.5, for T-joints, we studied a) the flow going straight on to the main pipe, and b) the flow going into the branch pipe. Again, we measured the pressure drop at low-medium pressure (< 1MPa) range for each fitting/flow. These data were applied to Equivalent Method (L_e/D) to see if this technique works for hydrogen applications.

Table 3 shows the test conditions for measuring the pressure drop. For each diameter, about 3 levels of pressure, and 10 - 20 levels of flow rate at low-medium pressure range were measured.

Fig.4 Test Bench for Analyzing Pressure Drop

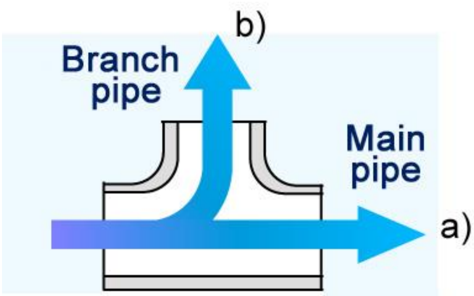


Fig.5 Flows in T-joints

Table 3 Test Conditions

Type of pipe	Straight pipe		Fitting (T-joints, Elbow joints)	
	Medium pressure (0.9, 0.7, 0.5, 0.3MPa)	Low pressure (0.09, 0.05, 0.02MPa)	Medium pressure (0.9, 0.7, 0.5, 0.3MPa)	Low pressure (0.09, 0.05, 0.02MPa)
40A*	NA	○	○	○
50A	○	○	○	○
80A	○	NA	○	NA
100A	○	NA	○	NA

○: Measured NA: Not measured *: Outer diameter = 48.6mm

c) Result of the Study

<Pressure Analysis Equations>

As shown in Fig.6, we confirmed that the data were consistent with generic flow analysis tools such as Colebrook equation, and/or AGA method, and also that by non-dimensionalizing the equations with Reynolds Number (*Re*), hydrogen could be analyzed quantitatively just the same way as other gasses. As a result, we derived the following equations to describe hydrogen behavior in low-medium pressure straight pipes.

$$\Delta P = K_p \left(\frac{TL}{D^5} \cdot \frac{Q_0^2}{2P_1} \right)$$ (Generic Equation)

$$K_p = 2,400 \times 10^{16} f \frac{zG}{z_0^2}$$

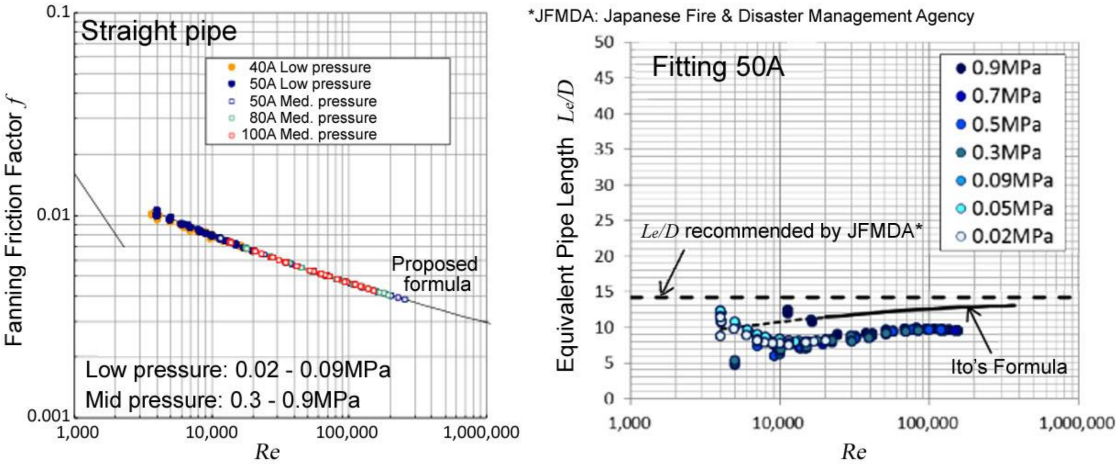
$$f = 0.231 \cdot (\log Re)^{-2.43}$$ (Proposed Equation) where, $10^4 < Re < 10^5$

ΔP : Pressure drop between input /output of the pipe	[MPa]
Q_0 : STP* mass flow rate	[Nm^3/h]
K_P : Pressure drop coefficient	[-]
T : Temperature	[-]
L : Length of pipe	[m]
P_1: Pressure at input of pipe	[MPaA]
D : Bore of pipe	[m]
Re : Reynolds Number	[-]
f : Fanning friction factor	[-]
G : Specific gravity (with respect to air)	[-]
z : Compressibility factor	[-]
z_0 : STP Compressibility factor	[-]

*: STP means standard temperature & pressure

<Pressure Drop Characteristics at Fittings>

Fig.6 shows the relationship between *Re* for 50A fittings, and their equivalent lengths. It was discovered that in the range of 0.02 – 0.9MPa, the equivalent length becomes shorter than what Fire Department's formula (approximation proposed by Japanese Fire & Disaster Management Agency; JFDMA) or Ito's formula would suggest, and it was confirmed that Equivalent Method could be applied to hydrogen in the same way as other fluids.



(a) *Re* vs. Friction Factor *f* (b) *Re* vs. *Le/D*

Fig.6 Measured Results of Pressure Drop

3) Safety Evaluation of Installation/construction of Gas Supply Equipment

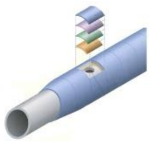
a) Scope of the Study

The purpose of this study is to define the emergency repair procedures, in case of a hydrogen leak from the pipeline. After identifying the location of the leak, a preliminary fix should be implemented to prevent secondary damage until the permanent fix is in place. Several repair options were tested to find out what would be suitable for hydrogen pipelines.

b) Summary of the Study

We tested four different types of seals; two kinds of rubber packing, multilayer shield, and self-bonding seal tape. With the exception of self-bonding seal, these are all commonly used in city gas applications.

Table 4 Types of Seals Tested

			
Rubber Packing A	Rubber Packing B	Multilayer Shield	Self-bonding Seal

To eliminate the influence of ambient temperature, the seal efficiency of each method was evaluated by measuring the pressure difference with a reference pipe, whose temperature was controlled to be same as the test object. Schematic diagram of this test apparatus is shown in Fig.8. A 10mm hole was punched into a polyethylene coated steel pipe (50A diameter) to simulate the leak. Pressure regulator was adjusted to give 10kPa of pressure, and the seal methods under test were applied to cover the hole. Table 5 shows the test conditions used in this evaluation.

Table 5　Conditions for Testing Seal Efficiency

Items	Conditions	Remarks
Fluid	Hydrogen (99.999%)	
Internal Pressure	10kPa (Higher than the assumed pressure in practical use)	Recent pressure requirement for hydrogen residential fuel cells: 6.0kPa Recent city gas supply pressure: 2.5kPa
Simulated leak diameter	10 mm	Corrosion pits: 1 - 2mm, Construction tool punctures: 5 - 6mm
Ambient Temperature	Room temperature (about 23℃), 40℃, -5℃	40℃, -5℃: Helium was used in this for safety reasons
Duration	5 hours	Maximum time assumed between detecting the leak point and disconnection thereof
Iterations	3 times per each condition	

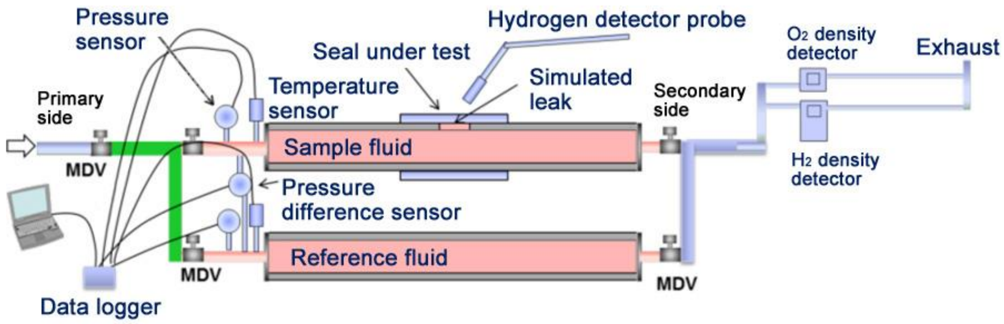


Fig.8　Drawing of Test Apparatus

c) Result of the Study

Even under the pressure of 10kPa, it was possible to apply all seal types to the simulated leak. Although fluid was blowing out from the test object, there was no trouble in installing the seal, and none took longer than usual to install. Rubber packing method, both A and B, were bolted, and multilayer shield was seal bonded to cover the leak. Installation time/procedure for these methods were consistent. However, to apply the self-bonding seal, it was necessary to stretch the tape and quickly wrap it around the leak. Depending on how strong the tape is stretched, the installation time/procedure tend to be unstable. In addition to this, there is a risk of rolling foreign objects inside during wrapping, and we figured that this would be another factor of uncertainty.

In this study, our priority was to find out what would be the proper measure for emergency fix, so we mainly focused on ease of installation and seal efficiency. The results are shown in Table 6. We were able to identify methods with sufficient performance in suppressing hydrogen leak.

Methods Tested	Evaluation Items				Overall Performance
	Ease of installation	Seal Efficiency			
		Room temperature	-5℃	40℃	
Rubber Packing A	Good	Good	Good	Good	Good
Rubber Packing B	Good	Good	Good	Good	Good
Multilayer Shield	Good	Good	Good	Good	Good
Self Bonding Seal	Fair	Poor	—	—	Poor

Table 6 Evaluation Results of Emergency Sealing Options

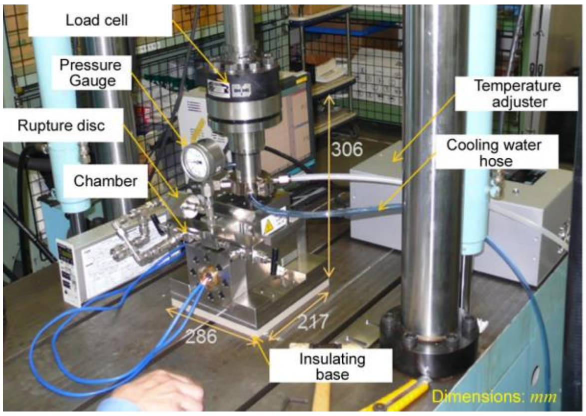
4) Research on Impact of Odorant Additive to Hydrogen Embrittlement of Metallic Material

a) Scope of the Study

Non-sulfuric odorants of record for hydrogen (2-hexenal, and cyclohexene) were tested to see if they would cause hydrogen embrittlement to metallic material. We employed fatigue crack propagation test for this.

b) Summary of the Study

We designed and built a test bench as shown in Fig.9, and ran a series of fatigue crack evolution tests. Materials to be tested are Carbon steel gas pipe (SGP), and Carbon steel pipes for pressure service (STPG), whose mechanical properties are shown in Table 7. These were placed under a) Hydrogen atmosphere, and b) Hydrogen atmosphere with odorant. Data were collected under each environment in different temperature conditions.



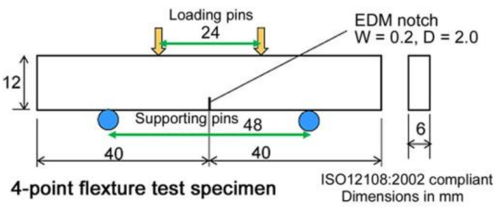


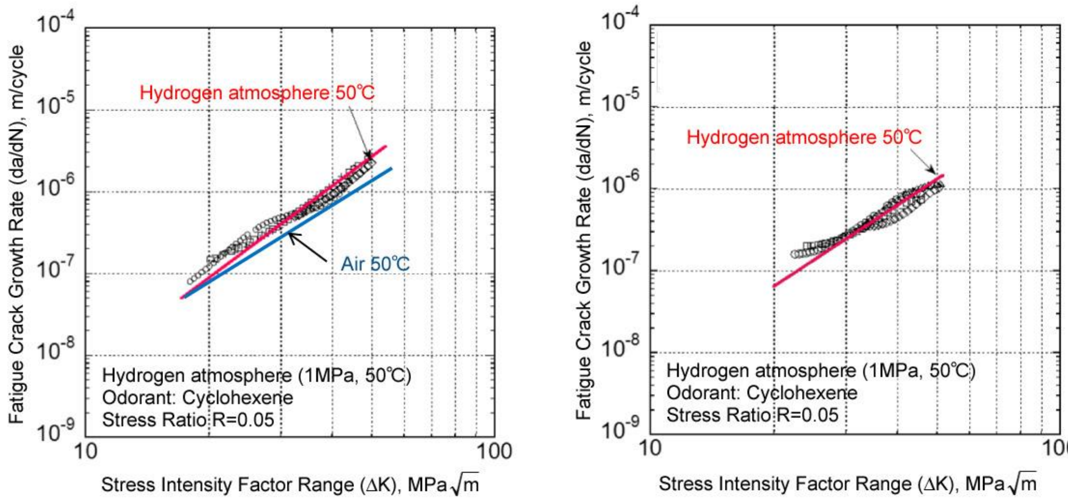
Fig.9 Photo of Fatigue Crack Propagation Test Apparatus with Shape and Dimension of Specimen

Table 7 Mechanical Properties of the Experimental Materials

Material	YS (MPa)	TS (MPa)	EL (%)
Carbon steel gas pipe (SGP)	329	436	38.6
Carbon steel pipes for pressure service (STPG)	288	477	38.1

c) Result of the Study

Fig.10 shows the results of fatigue crack evolution of SPG and STPG when exposed to cyclohexene as the odorant. No major difference was observed from hydrogen only atmosphere. This shows that cyclohexene odorants will not impact fatigue crack growth rate. Similar results were obtained with 2-hexenal odorant as well. However, it was seen that the crack propagation was significantly different in the air (See Fig.10 (a)).



(a) SGP (b) STPG

(Similar results were obtained with 2-hexenal)

Fig.10 Result of Fatigue Crack Propagation Test

4. Conclusion

While anticipating the future of Hydrogen Society, it is expected that hydrogen will be delivered through pipelines buried under public roads (with supply pressure < 1MPa). Under this circumstance, the scope of this project was to identify what technologies available today could be applied to hydrogen and to what extent.

In conclusion, important knowledge that will help assure safety of hydrogen delivery was obtained. The results of this study are expected to be utilized as the base data for establishing technical standards of the hydrogen delivery pipeline and systems.

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