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COMPORTEMENT DE L'EQUIPEMENT DE LA DISTRIBUTION
DU GAZ DANS LA LIVRAISON DE L'HYDROGENE

BEHAVIOR OF GAS DISTRIBUTION
EQUIPMENT IN HYDROGEN SERVICE

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RESUME

L'Institute of Gas Technology s'est acquitté des 2 ans d'un programme expérimental de 5 ans ayant pour objet d'étudier l'éventualité de livrer de l'hydrogène par les réseaux conventionnels de distribution du gaz. Nous avons construit et fait fonctionner trois systèmes de distribution "miniature" en nous servant d'éléments prêtés ou donnés à titre gracieux par des fabricants et des sociétés gazières. Les trois prototypes, à savoir: réseaux résidentiel, commercial, industriel, ont été exploités en laboratoire, et des essais de sécurité ont été faits, sous des conditions de contrôle serré, afin d'examiner et de comparer le débit de gaz et la décharge d'énergie, le rendement général des composantes, les fuites, pour le gaz naturel d'une part, et pour l'hydrogène d'autre part. Nous sommes en train d'examiner à l'heure actuelle toutes les composantes afin de noter les effets apparents de l'utilisation de l'hydrogène. Nous avons déjà observé de façon expérimentale que, dans les mêmes conditions de fonctionnement du même prototype de distribution, la décharge d'énergie dans le cas de l'hydrogène pourrait être de 80% celle du gaz naturel. Nous avons également mesuré des rapports volumétriques de fuites (hydrogène-gaz naturel) de 2,6:1 à 4,6:1 pour divers éléments des réseaux miniature. Nous n'avons découvert aucune condition parmi celles représentant les conditions normales d'exploitation de la distribution lors de laquelle l'hydrogène provenant d'une fuite s'enflammerait spontanément.

SUMMARY

The Institute of Gas Technology has completed 2 years of a 5-year experimental program to supply information about prospects for hydrogen delivery in conventional gas distribution systems. We have constructed and operated three "model" distribution systems using components loaned or donated by manufacturers and gas utility companies. The three models — Residential/Commercial, Industrial, and Safety Test — have been operated in the laboratory under closely controlled conditions to monitor and compare gas flow and energy delivery, general component performance, and leakage for natural gas and hydrogen. We are now in the process of examining specific components for any evident effects of hydrogen exposure. We have experimentally observed that energy delivery as hydrogen could be about 80% that of natural gas under the same operating conditions using a distribution model. We have also measured volumetric leakage

ratios (hydrogen-to-natural gas) of 2.6:1 to 4.6:1 for various different components in the model systems. We have not found any conditions corresponding to normal operating conditions of gas distribution where hydrogen will ignite spontaneously from a leak.

INTRODUCTION

This program is a multiyear effort to supply needed information about hydrogen delivery in natural gas distribution equipment. The immediate objectives are to identify operating, safety, and materials problems associated with the use of hydrogen in conventional distribution systems.

One of the major arguments for (nonfossil-based) hydrogen as a future supplement and eventual replacement for natural gas is the expectation that the existing gas delivery system can be used without major modifications. Natural gas constitutes a major portion of the energy used in the United States, now accounting for 20.9 EJ, or 25.4% of the U.S. energy consumption. The incentive for supplemental fuel gases (including hydrogen) to enable continued delivery of energy in fuel gas form is primarily financial. The embedded capital investment in the gas distribution industry in the United States now exceeds \$20 billion (10^9). This includes over 1 000 000 km of distribution mains, which carry gas to about 45 000 000 customers. Replacement of this distribution system with another would cost many times this investment. Furthermore, most equipment and lines now being installed are expected to last 50 years or longer.

If it is practical to carry hydrogen safely in this existing gas distribution equipment, then hydrogen is indeed an attractive form for energy delivery in the future. If moderate problems are identified now, then we will have sufficient time to define and develop alternative operating procedures. If serious problems are found, however, then other alternatives (besides hydrogen) must be weighed against major system modifications.

The experimental work described here is with pure (commercial cylinder grade) hydrogen, which is compared with both natural gas (96% methane) and pure methane. Pure hydrogen was chosen as the extreme case for the initial investigations, which have as the main objective to identify problem areas for the distribution of hydrogen in conventional natural gas equipment. Experiments with mixtures of hydrogen and natural gas are envisioned for later phases of this program.

1- CONSTRUCTION OF GAS DISTRIBUTION MODELS

During 1977 IGT constructed three model loops using gas distribution equipment loaned or donated by 15 manufacturers and utility companies. The 15 companies that are program participants (along with the U.S. Department of Energy) are listed in the "Acknowledgment" section of this paper.

All construction for the test loops was done in accordance with the utilities Construction and Material Specifications and the ASME Guide for Gas Transmission and Distribution Piping Systems — 1976. The two local gas utility companies and several of the participating manufacturers provided technicians and equipment to (1) weld steel joints, (2) fusion-join plastic piping, (3) hydraulically seal coupling, (4) make bell-and-spigot cast-iron joints, and (5) service meters. All subassemblies were leak-tested prior to and after integration into a total assembly or a test loop.

1.1- RESIDENTIAL/COMMERCIAL DISTRIBUTION MODEL

The Residential/Commercial Model Loop consists of four subloops and a bypass. The pipeline materials of construction are (1) steel, (2) copper, (3) plastic (high-molecular-weight, high-density polyethylene), and (4) cast iron. This model contains components and equipment normally installed in typical residential and/or commercial service. Figure 1 is a simplified diagram of this loop with its major equipment components. In operation, a single-stage compressor feeds 0.31 m^3(st)/h of natural gas or hydrogen to the model at a gauge pressure (Pe) between 4140 and 4480 mbar. The compressed gases pass through an aftercooler to reduce gas temperature to ambient and then through a surge tank to dampen pulsations.

A regulator reduces the gauge pressure to about 3450 to 4140 mbar, simulating pressures in the distribution mains and the service lines to commercial or residential consumers. With the cast-iron subloop the gauge pressure is reduced to 15 mbar by another pressure regulator. At the simulated building line, which is the termination of the service line, the distribution pressure (3450 to 4140 mbar) is reduced further by a service regulator to 15 mbar. The gases then pass through a gas meter to the inlet of the compressor and are recompressed and recycled. Flow is controlled and proportioned through the subloops with valves and the bypass.

1.2- INDUSTRIAL DISTRIBUTION MODEL

The Industrial Model consists of one loop and a bypass with steel pipeline material. This model contains components and equipment normally installed in typical industrial service. Figure 2 is a simplified diagram of this loop with its major equipment components. In operation, a two-stage compressor feeds 0.42 m^3(st)/h of natural gas or hydrogen to the model at a gauge pressure between 11 720 and 12 070 mbar. The compressed gases pass through an aftercooler to reduce gas temperatures to ambient, and then through a surge tank to dampen pulsations. A line regulator installation reduces the pressure to 4140 mbar, simulating pressures in the distribution main. Another regulator downstream, in series, reduces the (gauge) pressure further to 550 mbar, simulating the operating service pressures of industrial components. The gases then pass through several industrial gas meters (for example, diaphragm, rotary, or turbine) connected in series, to the inlet of the compressor, and then are recompressed and recycled. Flow is controlled and proportioned with valves and the bypass.

1.3- SAFETY TEST LOOP

The Safety Test Loop consists of one loop with a leak zone and a bypass. The leak zone provides a space for testing and defining problems associated with mechanical or corrosion leaks, leak clamps, and ruptures. The pipeline material is steel except at the leak zone. Figure 3 is a simplified diagram of this loop with its major equipment components. In operation, a single-stage compressor feeds 0.42 to 0.62 m^3(st)/h of natural gas or hydrogen to the loop at a gauge pressure between 3450 and 4140 mbar. The compressed gases pass through an aftercooler to reduce gas temperatures to ambient and then through a surge tank to dampen pulsations. The gases then pass through the experimental setup in the leak zone to the inlet of the compressor and are recom-

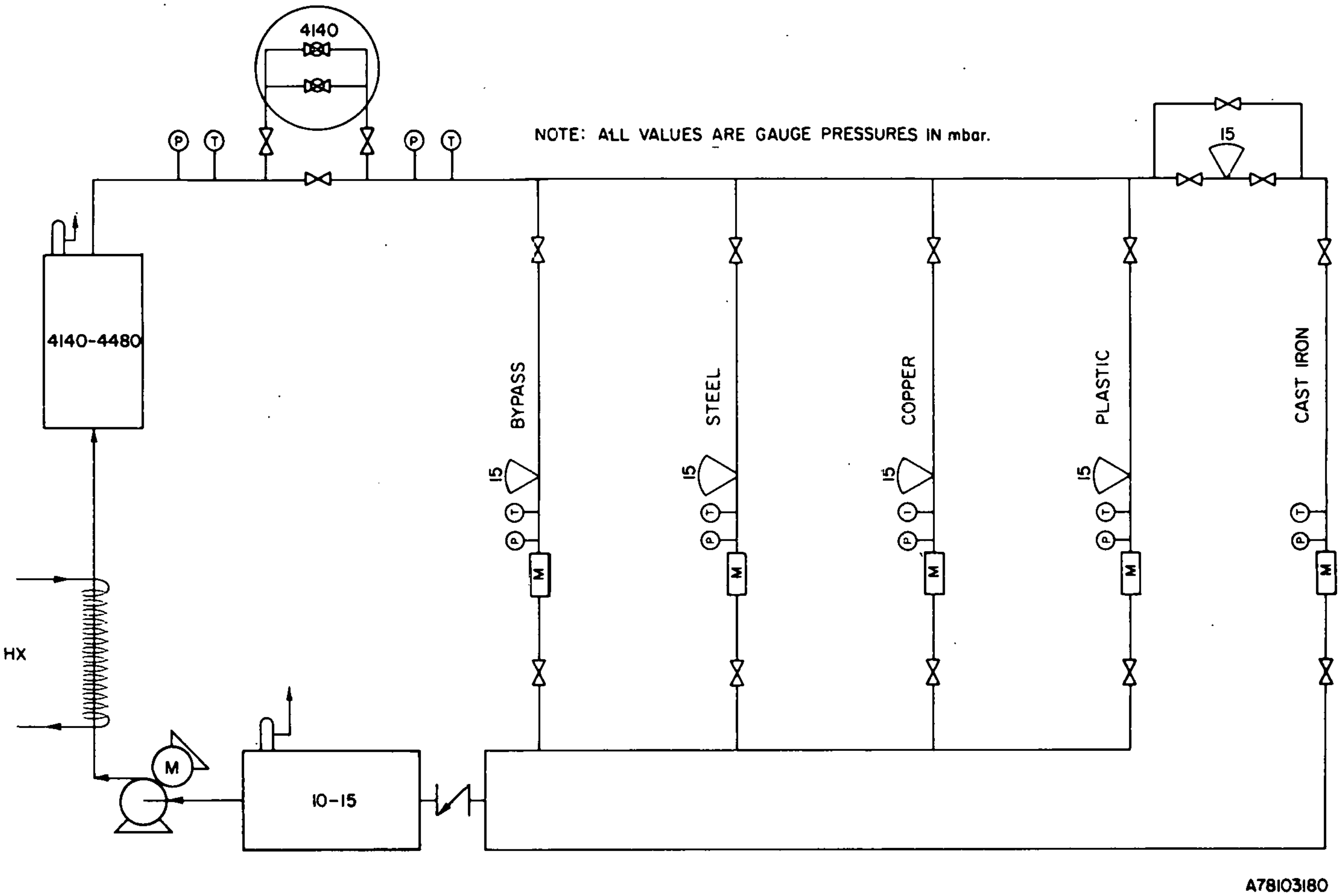

Fig. 1
Diagram of Residential/Commercial
Gas Distribution Model

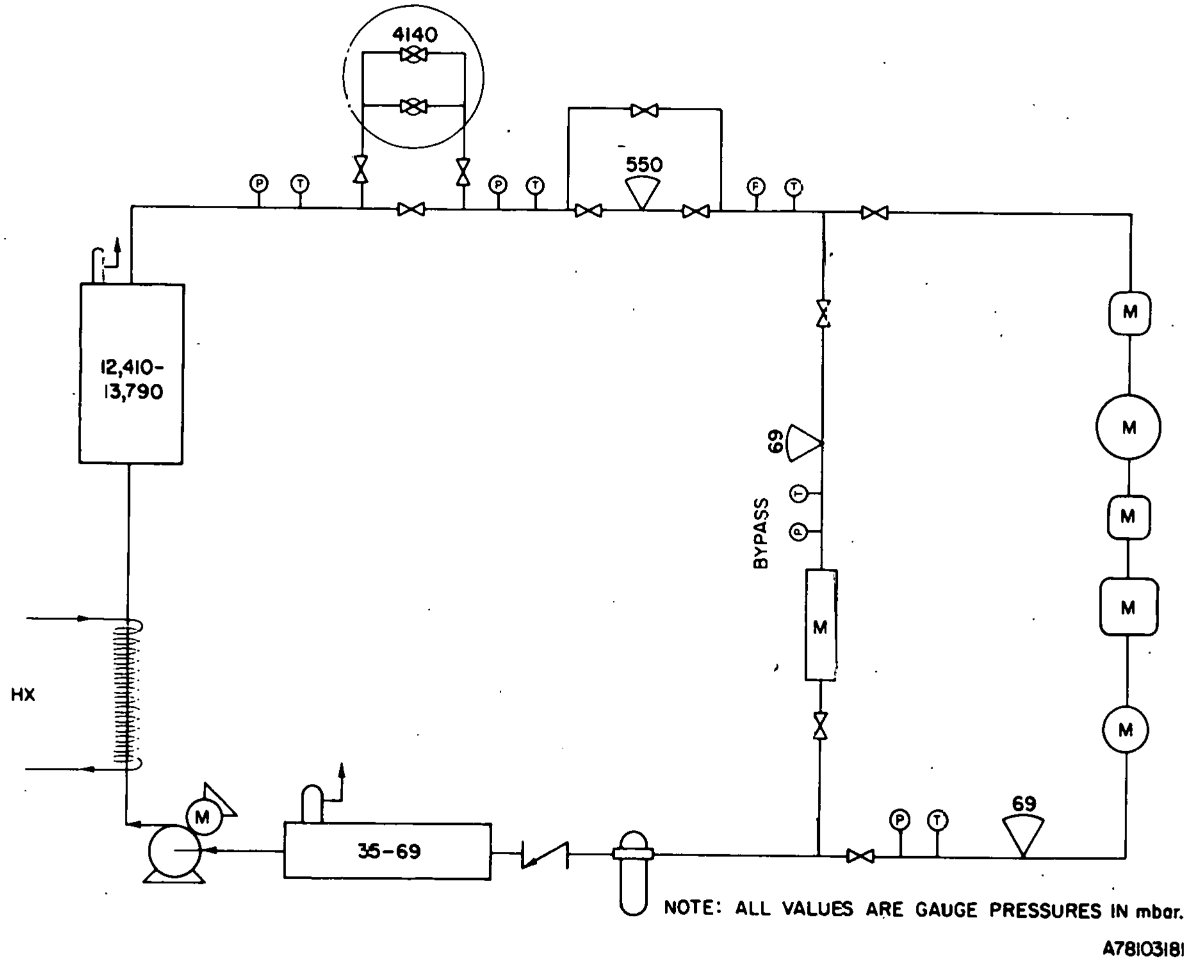

Fig. 2
Diagram of Industrial
Gas Distribution Model

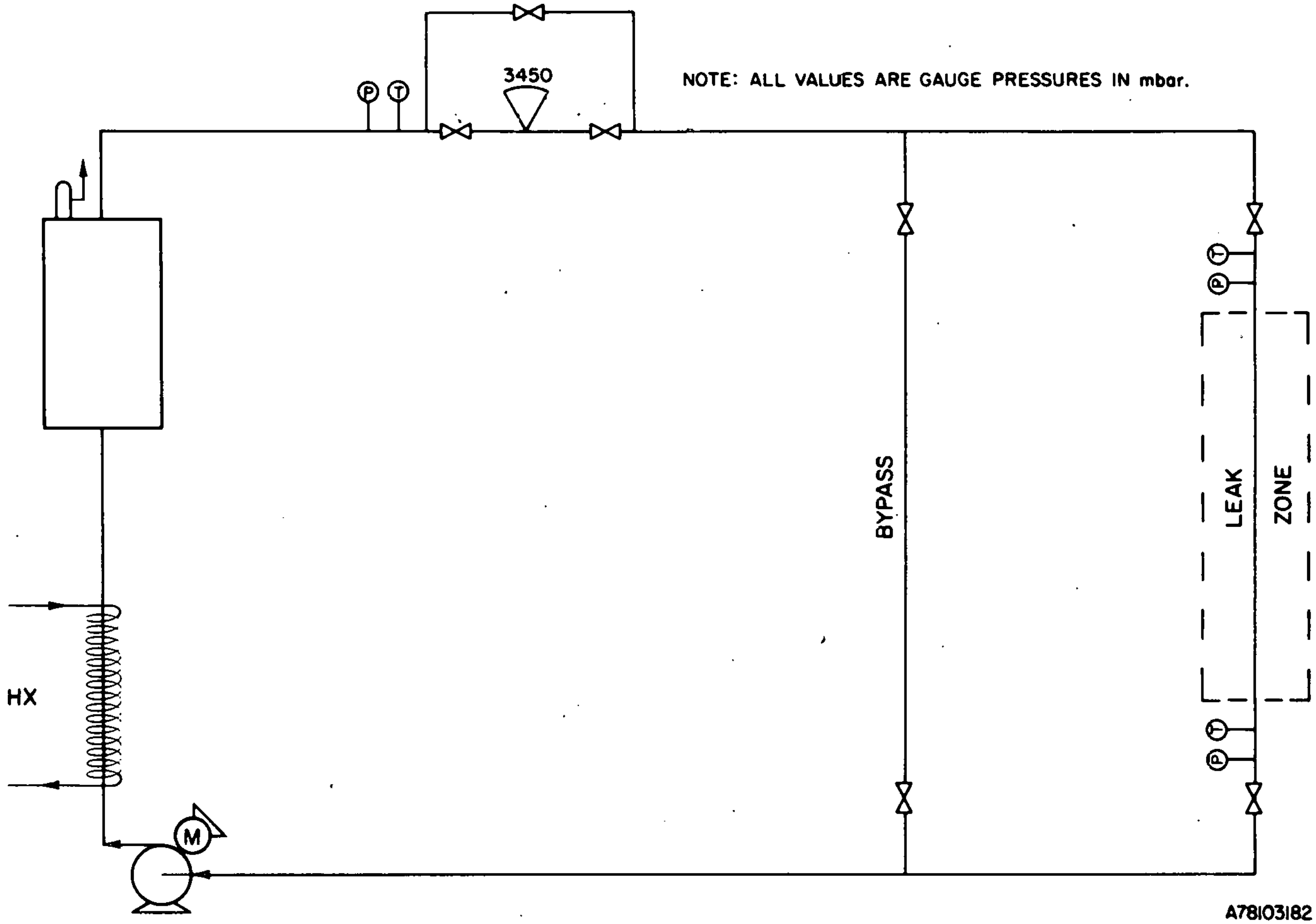

Fig. 3
Diagram of Safety Test Loop

pressed and recycled. If excess leakage is a problem, the gas flow terminates in the leak zone and the gases are vented to the outdoors.

2- OPERATION AND MEASUREMENT PROCEDURES

The three reciprocating piston compressors were installed to recycle and compress natural gas and/or hydrogen to the operating design conditions of the model test loops. An initial 40-hour test was performed with the Residential/Commercial and Industrial loops at design conditions using nitrogen gas. The systems operated satisfactorily, and leak rates of the components and model were characterized. During this operation it was again verified that both the systems and the individual components, fittings, and connections met industry requirements for leak-tightness.

The Residential/Commercial and Industrial models were then operated from 2 to 4 weeks to gain baseline data on flow and leakage with natural gas. Following this, both models were operated for 6 months on commercial-grade hydrogen. At this writing, we are in the process of examining equipment and components of the Industrial Test Loop for physical, chemical, or metallurgical effects due to 6 months of hydrogen exposure. Each individual component has a duplicate that is stored in original condition. These were supplied by the participating gas companies or manufacturers for comparison with the hydrogen-exposed components. So far, no materials problems or incompatibilities in the distribution equipment are evident.

By means of various regulators or stations in the two major loops, the operating pressures are reduced as the gases pass from the feeder main (10.35 to 13.80 bars), to the distribution main (3450 to 4140 mbar), and to the point of service (345 to 690 mbar for the Industrial Loop and 15 to 25 mbar for the Residential/Commercial Loop). Meters are installed either in series or in controlled subloops so that comparative flow measurement data (on natural gas and hydrogen) can be taken. At a simulated building line, the gases are filtered, recompressed, and recycled to the loops. The Residential/Commercial and Industrial models are designed to operate continuously, whereas the Safety Test Loop operates when special (leakage) tests are performed. Using local pressure and temperature measurements, all gas flows are reduced mathematically to industry standard conditions (m^3, 15°C, 1013.25 mbar).

Eleven components (couplings, unions, a pressure regulator, and a flow meter) are provided with sheet metal or Plexiglas enclosures to monitor and compare leakage of natural gas and hydrogen from these specific components. Volumetric displacement (of liquid) and gas analysis (by gas chromatography or mass spectrograph) were the methods selected to measure the leak rates of these components.

Total system leakage is determined by measuring makeup gas additions to the high-pressure side of the test loops (after the compressor). The makeup gas quantities are being determined by pressure decay from calibrated cylinders.

3- PRELIMINARY OBSERVATIONS AND RESULTS

The hydrogen-to-natural gas volumetric flow ratio can be predicted for laminar and turbulent flow by using equations for gas flow. Empirical (transmission or distribution) pipeline factors can be included, and the ratios of energy delivery can likewise be predicted by incorporating the different heating values (calorific content) for hydrogen and natural gas. Also, leakage ratios can be calculated for diffusional flow (by using the square root of the ratio of molecular weights) and for streamline flow through an orifice (from the Bernoulli theorem). However, the gas properties, which differ widely between hydrogen and natural gas or methane, and the importance of even slightly different operating conditions make experimental measurement and confirmation, when possible, very necessary for gas distribution components and systems.

3.1- GAS FLOW AND ENERGY DELIVERY

The high heating value of hydrogen is 12.1 MJ/m^3(st), whereas natural gas heating values are commonly in the range of 35.3 to 41 MJ/m^3(st). Thus, the flow of hydrogen must be increased by a factor of about 2.9 to 3.4 (relative to natural gas under the same temperature and pressure conditions) to deliver energy at a rate equivalent to that of natural gas. A previous study (1) considered the gas flow equations for laminar, partially turbulent, and turbulent flow hydrogen and natural gas in pipes.

Some notable differences between hydrogen and methane with respect to gas flow and energy delivery are outlined below.

	Units	H_2	CH_4
(High) Heating Value	MJ/m^3(st)	12.1	37.6
Viscosity	Pa s	8.5	11.0
Specific Gravity	--	0.07	0.55

For laminar flow, i.e., Reynolds number (Re) < 2000 —

$$\text{avg flow velocity } H_2 = 1.3 \times \text{avg flow velocity } CH_4$$

$$Re_{H_2} = 0.2\ Re_{CH_4}$$

For partially turbulent flow (2000 < Re < 10^5) —

$$\text{flow velocity } H_2 = 2.6 \times \text{flow velocity } CH_4$$

$$Re_{H_2} = 0.4\ Re_{CH_4}$$

For turbulent flow (Re > 10^5) —

$$\text{flow velocity } H_2 = 2.9 \times \text{flow velocity } CH_4$$

$$Re_{H_2} = 0.5\ Re_{CH_4}$$

Some conclusions of the previous study (referenced above) follow:

> Usually, the natural gas flow in distribution mains is partially turbulent, but conditions of laminar and fully turbulent flow occur. If hydrogen is to be delivered in this or a future system built for natural gas service, certain operating and procedural changes are to be anti-

cipated. If volumetric flow rates for hydrogen were about 325% (on the average) of those for natural gas, an equivalent amount of energy would be delivered. However, if the pipes and operating pressures are <u>unchanged</u> –

- For laminar flow, the volumetric flow rate of hydrogen will be about 130% of that of natural gas and the delivered energy will be only 40% of that of natural gas.
- For partially turbulent flow, the volumetric flow rate of hydrogen will be about 260% of that of natural gas and the delivered energy will be 80% of that of natural gas.
- For turbulent flow, the volumetric flow rate of hydrogen will be about 280% of that of natural gas and the delivered energy will be 85% of that of natural gas.
- For all categories of flow, the Reynolds number for hydrogen will be one-half or less than that of natural gas, and the designed-for categories of flow might be downgraded, e.g., partially turbulent to laminar, in some instances.
- To deliver the same quantity of energy, the hydrogen gas density is best increased by increasing the operating pressures of the pipelines.

In our experiments with the Residential/Commercial Distribution Loop operating on hydrogen, we adjusted the pressures so that the capacities of the residential meters would be balanced and not exceeded. With the adjustments (by valve throttling and/or service regulator spring adjustments), we attained a volumetric hydrogen flow rate of about 300% that of methane. Methane has a heating value of 37.6 MJ/m^3(st). Adjustments in energy delivery to about 97% that of methane were made, which were within the operating range of valves, regulators, and meters.

In our experiments with the Industrial Distribution Loop operating on hydrogen, the volumetric flow rate was about 245% that of natural gas (98% methane, 37.2 MJ/m^3[st]) without making any adjustments. Hence, the energy delivery with hydrogen was 80% that of natural gas under the same operating conditions with this model. Although a direct comparison to an equivalent length of pipe may not be valid, this observation tends to substantiate the predicted case of partially turbulent or turbulent flow.

Comparative flowmeter readings in the Industrial Loop are presented in Table 1 for tests on natural gas and hydrogen (a 534-hour cumulative test on natural gas and 935 and 1170-hour cumulative tests on hydrogen). All meters are of a different brand (manufacturer): The mean value of the average flow rates is 6.72 m^3(st) for natural gas, 15.75 m^3(st)/h for hydrogen (Test 1), and 16.43 m^3(st)/h for hydrogen (Test 2).

Table 1. Comparative Flowmeter Readings in Natural Gas and Hydrogen Operations

	Natural Gas (534 Hours)		Hydrogen Test 1 (935 Hours)		Hydrogen Test 2 (1170 Hours)	
Mean Flow Rate,* m^3/h	6.72		15.75		16.43	
Sample Standard Deviation,* %	4.3		14.1		12.7	
	Average Flow Rate, m^3/h	Deviation From Mean, %	Average Flow Rate, m^3/h	Deviation From Mean, %	Average Flow Rate, m^3/h	Deviation From Mean, %
Turbine, 4000 CF/hr	6.613	–1.7	15.11	–4.0	16.50	–2.6
Diaphragm No. 1, 1000 CF/hr	6.876	+2.2	16.17	+2.7	17.32	+2.3
Diaphragm No. 2, 1000 CF/hr	6.657	–0.8	15.46	–1.9	16.71	–1.3
Diaphragm No. 3, 1000 CF/hr	6.590	–2.0	15.36	–2.5	16.56	–2.2
Rotary, 3000 CF/hr	6.763	+0.5	16.00	+1.7	17.16	+1.3

* Based on the three diaphragm meters and the rotary meter.

3.2 GAS LEAKAGE — HYDROGEN VERSUS NATURAL GAS

Figure 4 presents baseline natural gas leakage data for the Industrial Model, and Figure 5 presents hydrogen leakage data under the same conditions. To determine the leakage of a test loop, the compressor leakage is subtracted from the combined system leakage. In the Industrial Loop experiments, the overall natural gas loop leakage rate was determined to be 2.0 dm^3(st)/h and the overall hydrogen loop leakage rate was found to be 6.40 dm^3(st)/h. Therefore, the observed volumetric leak ratio is 6.40/2.0 = 3.20. In terms of energy loss via leakage, the ratio is (3.2 x 12.1)/37.2 = 1.04 (energy lost as hydrogen to energy lost as natural gas).

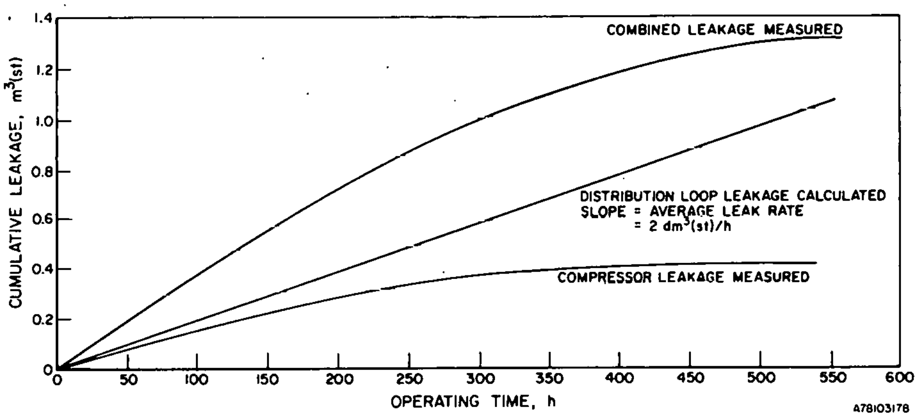

Fig. 4
Natural Gas Leakage (Cumulative)
of the Industrial Model

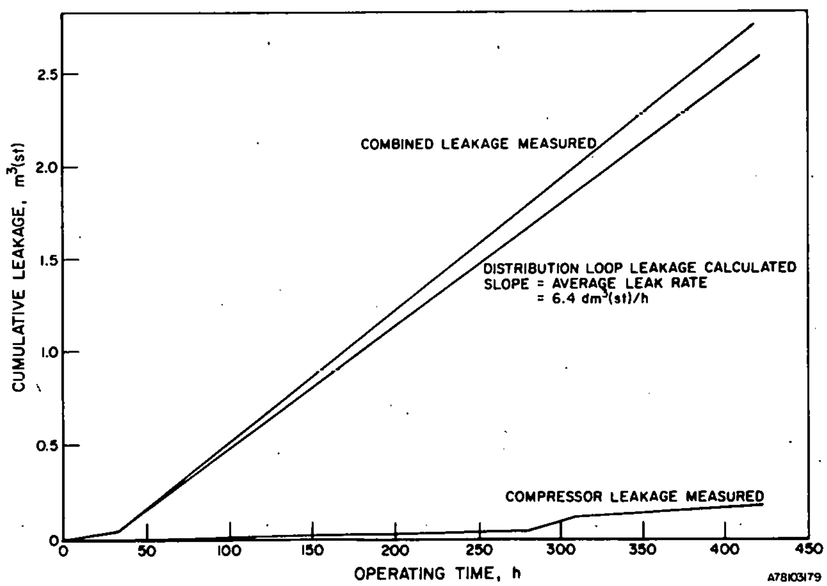

Fig. 5
Hydrogen Leakage (Cumulative)
of the Industrial Model

The volume of the Industrial Model is about 0.71 m^3, and the circulation flow rate is 25.5 m^3(st)/h. Hence, the average leakage of hydrogen "per pass" through the loop is 6.4 dm^3(st)/h ÷ (25.5/0.71 passes/h) = 0.18 dm^3(st)/pass, or about 0.025% per pass.

Figure 6 presents baseline natural gas leakage data, and Figure 7 presents hydrogen leakage data for the Residential/Commercial Loop, operating under the same conditions. The overall natural gas loop leakage was determined to be 0.363 dm^3(st)/h, and the overall hydrogen loop leakage, 1.22 dm^3(st)/h. The observed volumetric leak ratio for the Residential/Commercial Loop is 1.22/0.363 = 3.36, and the energy loss ratio is (3.36 x 12.9)/37.6 = 1.08.

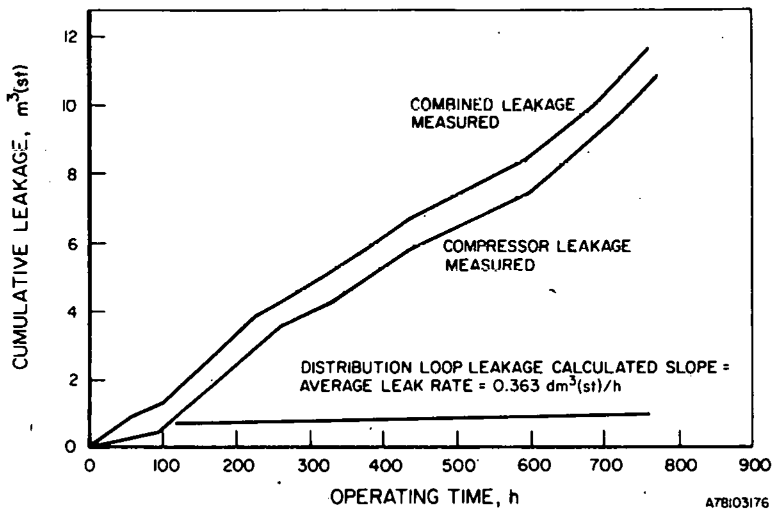

Fig. 6
Natural Gas Leakage (Cumulative) of the Residential/Commercial Model

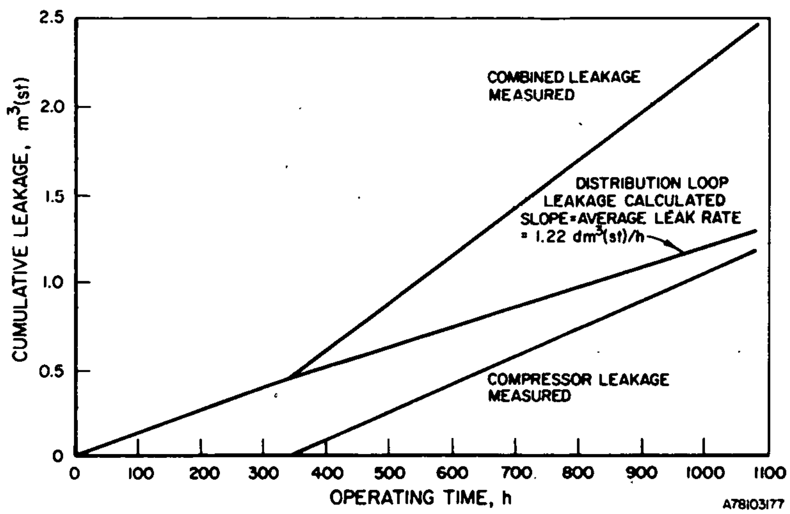

Fig. 7
Hydrogen Leakage (Cumulative) of the Residential/Commercial Model

The volume of the Residential/Commercial Model is about 1.19 m^3, and the average leakage of hydrogen "per pass" is 0.079 dm^3(st)/h, or about 0.007% per pass.

Figures 4 through 7 show three notable aspects of system leakage:

1. The model loop leakage rates are quite small.

2. Loop leakages are relatively constant, and no significant new leakage appears to be developing with time.

3. Compressor leakage increases with time as rings and seals wear.

Table 2 lists and compares natural gas and hydrogen leakage observed with the components enclosed. The hydrogen-to-natural gas leak ratio ranged from 2.61:1 to 4.64:1. In general, the leakage is very small (less than 10 cm^3 per day for natural gas or hydrogen) for all of the enclosed components except for the 2-inch threaded pipe coupling. We had determined from the assembly checkout tests and the onset of testing that threads on this particular 2-inch pipe coupling joint were damaged and that leakage would probably be significant (in this case, 13% to 17% of Residential/Commercial Loop leakage). Although more data are being collected, preliminary indications are that rubber coupling seals and valve-stem seals are exhibiting leakage rates 4 to 5 times higher for hydrogen than for natural gas.

3.3- SPECIAL LEAK TESTS

A section of the Safety Test Loop was fitted with 1-inch-ips plastic pipe with three simulated leak holes (3.175, 1.58, and 0.76 mm diameter). Hydrogen at a flow rate of 39.2 m^3(st)/h and a gauge pressure of 3795 mbar in the pipe section was allowed to escape through each hole, separately, and the temperature of the escaping hydrogen stream was monitored with a thermocouple and a strip-chart recorder.

The data indicate that the process of expansion of hydrogen through a hole in a pipe is dominated by an adiabatic expansion similar to that through a nozzle. Hydrogen is noted for peculiar behavior during isenthalpic expansion; it heats because its Joule-Thomson inversion temperature is 202 K, whereas for natural gas this inversion temperature is 950 K. However, the observed expansions through the created leaks coincided with a cooling of the gas generally. Only at certain points in the leaking gas stream very near the hole did there appear to be some Joule-Thomson isenthalpic expansion effects that would account for observed hydrogen temperatures being 1° or 2°C above ambient. These effects are not significant and would not inititate autoignition of a hydrogen leak.

The hydrogen leak from the 0.76-mm hole was ignited with a match. The leak ignited instantly and exhibited a slightly visible flame about 15 cm long. The flame did not damage the plastic pipe while supplied with an internal pipe gauge pressure of 3795 mbar. When the pressure to the test section was turned off, the pressure in the test section decayed and the hydrogen flame softened, shortened, and began to melt the pipe at the leak hole. At this point the flame was extinguished with a wet rag. After the ignition test, the pipe around the leak hole felt warm to the touch.

Table 2. Residential/Commercial Model Enclosed Component Leak Rates

Component	NG* Leak Rate			H_2 Leak Rate	H_2 Leak Rate/NG Leak Rate		
	Test 1 (352 hr)	Test 2 (457 hr)	Average	Test 1 (933 hr)	H_2 Test 1/ NG Test 1	H_2 Test 1/ NG Test 2	H_2 Test 1/ NG Average
	cm^3/24-hr day						
2-in. hydraulically applied coupling; rubber seal on steel pipe	0.079	0.127	0.103	0.362	4.58	2.85	3.51
2-in. coupling with 3-bolt construction; rubber seal on steel pipe	0.051	0.079	0.065	0.206	4.04	2.61	3.17
2-in. weld joint; steel pipe	0	0	0	0	--	--	--
2-in. hydraulically applied transition coupling; rubber seal on polyethylene and steel pipe	0.74	0.94	0.84	3.43	4.64	3.65	4.08
2-in. pipe thread coupling; steel pipe	--	1100**	1100**	4900**	--	4.45	4.45
2-in. insulating joint; steel pipe	<10**	<10**	<10**	<10**	--	--	--
2-in. compression coupling; steel pipe	<10**	<10**	<10**	<10**	--	--	--
2-in. flanged joint with asbestos gasket	<10**	<10**	<10**	<10**	--	--	--
Residential service regulator	<10**	<10**	<10**	<10**	--	--	--
Residential meter	<10**	<10**	<10**	<10**	--	--	--
2-in. insulating union with threaded ends; steel pipe	<10**	<10**	<10**	<10**	--	--	--

* NG = natural gas.

** Instantaneous leak rate by the bubble piston method; 10 cm^3/day minimum detectable leakage.

CONCLUSIONS

The current natural gas distribution system is an effective method for delivering fuel gas to residential, commercial, and industrial consumers. It has evolved over decades, is comprised of many different materials of construction, and operates at pressures from millibars up to several bars. If the operating pressures and distribution piping are not changed, we conclude the following for hydrogen delivery:

- Under (normal) turbulent flow conditions, hydrogen energy delivery will be 80% to 90% of natural gas energy delivery; this is experimentally confirmed.

- Under laminar flow conditions, hydrogen energy delivery might be only about 40% of natural gas energy delivery. This is a potential problem area still subject to experimental verification.

- The overall hydrogen-to-natural gas leak ratio for a distribution system will be about 3.25:1, and the overall energy loss ratio will be about 1.04:1. The hydrogen-to-natural gas leak ratio for individual components will range from 2.5:1 to 5:1, depending upon the permeation characteristics of the material of construction and the joining methods.

- Hydrogen leaks will not ignite spontaneously; hydrogen escaping from a leak expands somewhat adiabatically and cools.

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