

Development of Fuel Economy Measurement Method for Fuel Cell Vehicle

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ABSTRACT

A practical fuel economy measurement method has been developed for fuel cell vehicles. The weight method was selected for study from among the various fuel economy measurement methods available for pure hydrogen-type fuel cell vehicles as a direct measurement method, which was accurate and could be produced at a comparatively low cost. Solutions were provided to the drawbacks of measurement deviations caused by pressure variations in the fuel pipes and lowered hydrogen purity due to air entering the pipes. This development project assisted in fuel economy measurements for the Honda FCX, the world's first market-ready fuel cell vehicle; it also provided the measurement system for the Environmental Protection Agency (EPA) tests of the same vehicle, which resulted in the world's first confirmatory test of a fuel cell vehicle.

1. Introduction

In the development of fuel cell vehicles in recent years, there has also been a desire for the development of methods to evaluate performance^{(1),(2)}. In the USA, particularly, in order to respond to official confirmatory tests for pure hydrogen fuel cell vehicles carried out by the EPA (Environmental Protection Agency), it was absolutely essential to develop a fuel economy measurement method that was both highly accurate and practical⁽³⁾.

One international standard of fuel economy measurements for internal combustion engines, such as gasoline or diesel engines, is the "carbon balance method" utilizing the fact that the amount of carbon is the same in the intake and exhaust. By measuring the amount of carbon in the exhaust gases, it is possible to determine the amount of fuel consumption. However, with a fuel cell vehicle, that principle cannot be applied, and each manufacturer has adopted their own measurement method. In this development project, a comparative study was made of various fuel economy measurement methods used for pure hydrogen fuel cell vehicles, which are the most desired in development, and an attempt was made to develop a measurement method that can lead to the manufacture of a device that is highly accurate and can be used universally, at a comparatively low cost.

2. Development Goals

There were four development goals.

- (1) Measurement Accuracy
In the US fuel economy measurement modes of City and Highway, measurement accuracy in the SAE-J2572 standards stipulated by the SAE (Society of Automotive Engineers) must be $\pm 1\%$.
- (2) Universal Use
It must be possible to use the method both in Japan and in the USA. It must be possible to measure the amount of fuel consumption for each phase, even in modes composed of multiple phases, such as the US certification fuel consumption mode.
- (3) Cost of Manufacture
It must be able to be manufactured at a cost lower than the fuel consumption measurement equipment gasoline vehicles use, the carbon balance method, at no more than ¥2 million.
- (4) Standardization
Used for the official confirmatory test, the fuel economy value given in the test results must be recognized as an official value.

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3. Selection of Measurement Method

3.1. Representative Measurement Methods

3.1.1. Weight method

This is a method that directly measures the mass of the pure hydrogen fuel, and this principle is used as a calibrated standards method in gasoline vehicle carbon balance methods as well. If one uses a measurement instrument that is highly accurate and does not often cause deviations, one can expect good measurement accuracy. But, there are the issues of deviations caused by pressure changes in the fuel supply pipes and of a drop in hydrogen purity within the pipes due to air contamination when the hydrogen tank was connected. Specifically, the mass of the hydrogen tank, prepared for measurements as shown in Fig. 1, is measured before and after the tests, and the fuel consumption is determined from the difference in the masses. Fuel consumption W (g) is calculated using Eq. (1) below.

$$W = W_i - W_f \quad (1)$$

W_i : Mass of hydrogen tank before test (g)

W_f : Mass of hydrogen tank after test (g)

3.1.2. Flow method

This method measures fuel consumption by continuously measuring fuel supply flow and integrating the measurements. There are no deviations due to pressure changes within the pipes, but there are the issues of accuracy at transient times and at very low flow rate, or when deviations are integrated. Specifically, the value detected by Flow Meter 1 shown in Fig. 1 is integrated, and the fuel consumption W (g) is calculated according to Eq. (2).

$$W = \frac{\sum Q}{22.414} \times m \quad (2)$$

Q : Flow rate of fuel (NL/sec)

m : Molecular weight of hydrogen 2.016 (g/mol)

3.1.3. P/T method (pressure method)

Before and after the tests, the hydrogen tank's pressure and temperature are measured, and the fuel consumption is calculated from the ideal gas equation, etc. Specifically, the pressure and temperature of the hydrogen tank are measured before and after the tests using a pressure gauge and thermometer, as shown in Fig. 1. Fuel consumption is calculated using the idea gas equation, etc., from the changes before and after. Deviations occur due to variations of pressure within the pipes, which is a common source of deviation. Fuel consumption W (g) is calculated using Eq. (3) below.

$$W = \left(\frac{P_i \times V}{R \times T_i} - \frac{P_f \times V}{R \times T_f} \right) \times m \quad (3)$$

P_i : Hydrogen tank pressure before tests (Pa)

P_f : Hydrogen tank pressure after tests (Pa)

T_i : Hydrogen tank temperature before tests (K)

T_f : Hydrogen tank temperature after tests (K)

V : Hydrogen tank capacity (m^3)

R : Gas constant 8.314 (J/mol·K)

m : Molecular weight of hydrogen 2.016 (g/mol)

3.1.4. Electrical current method

Utilizing the principle that the electrical current output from the fuel cell stack is proportional to the fuel consumption used in generating electricity, the values detected by the current sensor shown in Fig. 1 are integrated, and fuel consumption calculated. With this method, there are no deviations due to variations in pressure inside the pipes, and accuracy when transient can also be expected. However, depending on the test vehicle, it is also necessary to measure, using a flow method or something similar, the hydrogen that is exhausted without being used to generate electricity, called "purged hydrogen". Therefore, there are many issues such as error integration similar to the flow method, or water elimination in the purged hydrogen, etc. The fuel consumption W (g) is calculated using Eq. (4) when the purged hydrogen portion is measured using Flow Meter 2 shown in Fig. 1.

$$W = \frac{n \times m \times \sum I}{F} + \frac{\sum Q_p}{22.414} \times m \quad (4)$$

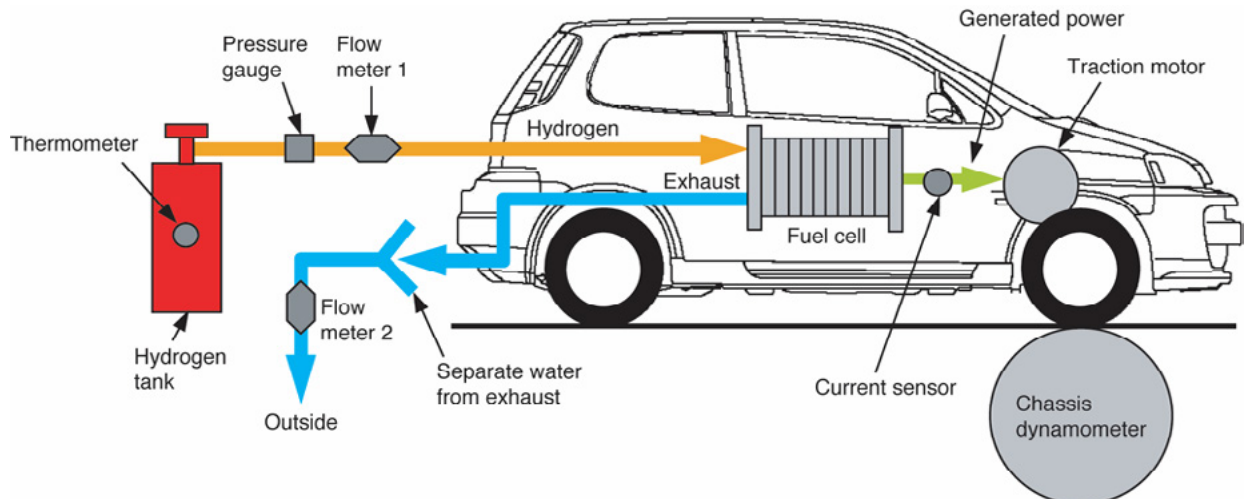


Fig. 1 Comparison of various method

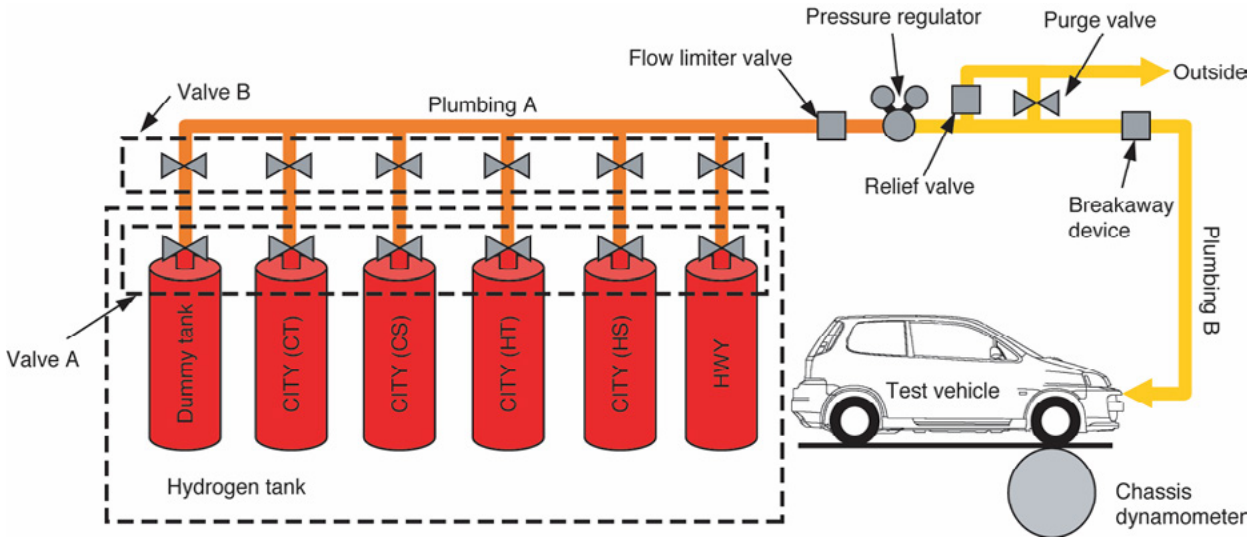


Fig. 2 Configuration of weight method system

I : Fuel cell output current (A)
 n : Number of cells in the fuel cell
 F : Faraday constant 9.64867×10^4 (C/mol)
 m : Molecular weight of hydrogen 2.016 (g/mol)
 Q_p : Purged hydrogen flow rate (NL/sec)

3.2. Adoption of the Weight Method

For the following reasons, the weight method was adopted in this development project.

- (1) Because the hydrogen being measured is measured only in a direct manner, there is essentially little cause of deviation.
- (2) It has become comparatively easy to obtain an accurate measurement device.
- (3) The outlook is good for countermeasures concerning the hydrogen remaining inside the pipes.

4. Measurement Accuracy

The major factor affecting weight method measurement accuracy is deviations due to pressure variations within the pipes. In addition, there is the issue of a drop in hydrogen purity due to air contamination in the pipes during hydrogen tank connection. The following countermeasures were taken, for these issues.

Because deviations due to pressure variations within the pipes occur in pressure difference before and after tests, as shown in Fig. 3, deviations can be reduced by maintaining a fixed pressure in the pipes before and after testing. Therefore, as shown in Fig. 2, the pressure in the pipes is raised to a specific pressure prior to the test by using a dummy tank, without using the hydrogen in the measurement tank. By having a pressure regulator in the pipes close to the hydrogen tanks, although pressure variations remain in Plumbing A, as shown in Fig. 2, there is no pressure variation in Plumbing B, and deviation is reduced. The pressure regulator's pressure reduction amount must be set so that supply pressure does not drop below the minimum pressure needed by the vehicle, including that during acceleration and deceleration. It was confirmed that, in both the City and Highway modes shown in Figs. 4 and 5, that the supply pressure for the test vehicle Honda FCX was at least 0.7 MPa, which is the minimum pressure required.

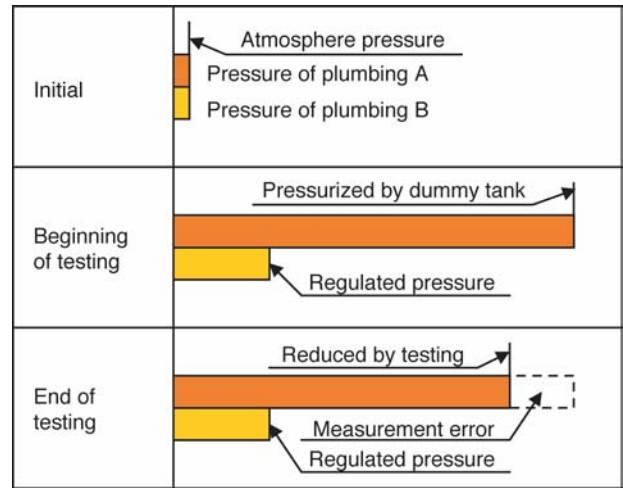


Fig. 3 Plumbing pressure and measurement deviation

By adding a dummy tank and a pressure regulator, measurement deviations caused by pressure variation within the pipes are reduced, and the effects shown in Figs. 6 and 7 are obtained. In the end, it is capable to fully meet the measurement accuracy of $\pm 1\%$ required by SAE standards. As shown in Fig. 8, the measurement accuracy for each phase of the City modes meets the SAE standards. In order to clarify the effect of each of these countermeasures, Figs. 6, 7, and 8 shows the absolute values of the deviations.

Concerning the hydrogen fuel supplied to fuel cell vehicles, because generally an extremely pure hydrogen – 99.99% class – is required, it is necessary to take appropriate countermeasures to prevent even the smallest amount of air penetrating the pipes when the hydrogen tanks are connected. Therefore, as shown in Fig. 2, by repeatedly discharging the hydrogen fuel in the dummy tank to the outside through the purge valve, any air between Valve A and Valve B is eliminated, without using hydrogen from the hydrogen tank used for measurement. Figure 9 shows the number of these air purging cycles and the purity of hydrogen within the pipes. At three or more cycles, the hydrogen purity in the pipes reaches 99.99% or higher, and the required accuracy is roughly achieved.

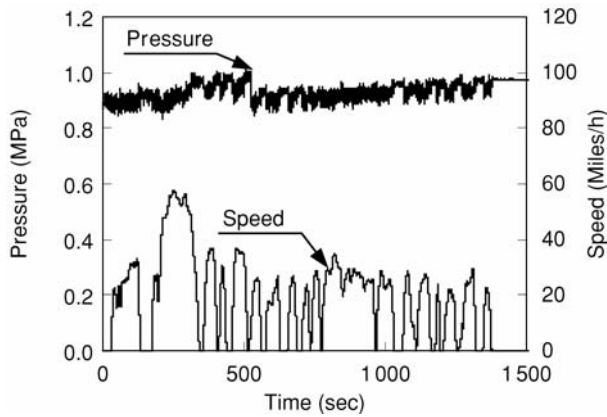


Fig. 4 Fuel supply pressure (CITY)

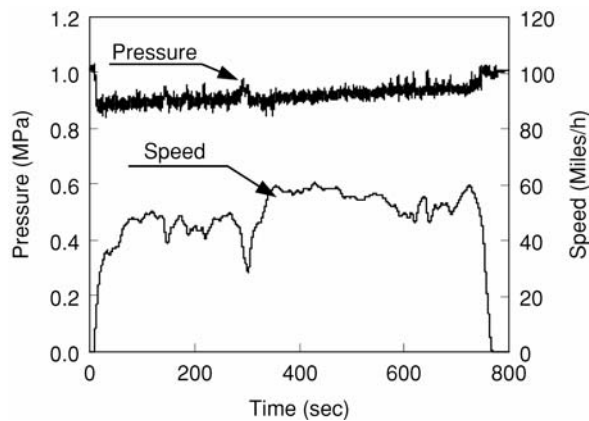


Fig. 5 Fuel supply pressure (HWY)

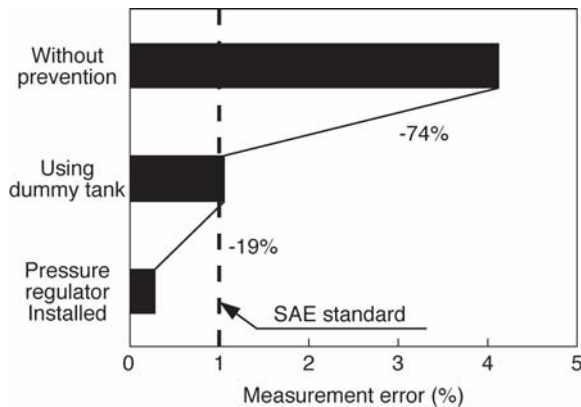


Fig. 6 Measurement deviation (CITY)

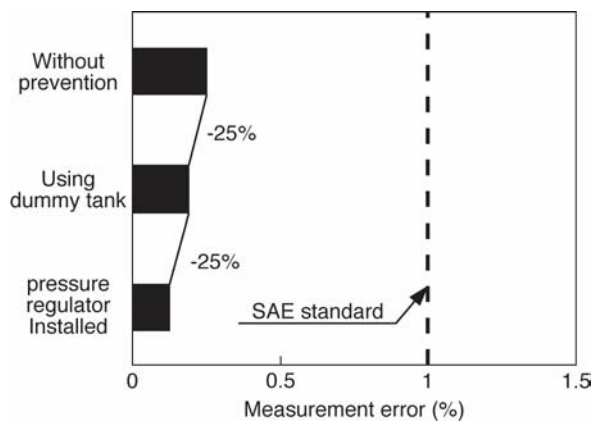


Fig. 7 Measurement deviation (HWY)

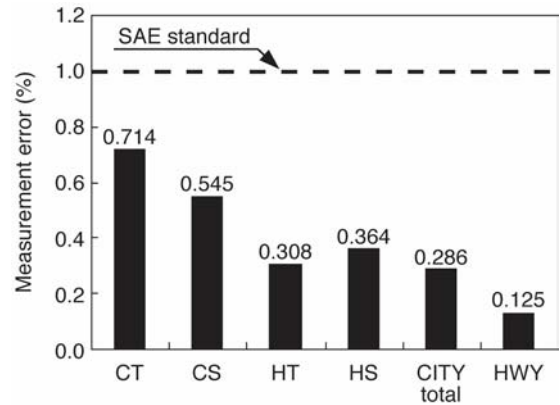


Fig. 8 Measurement deviation for each phase

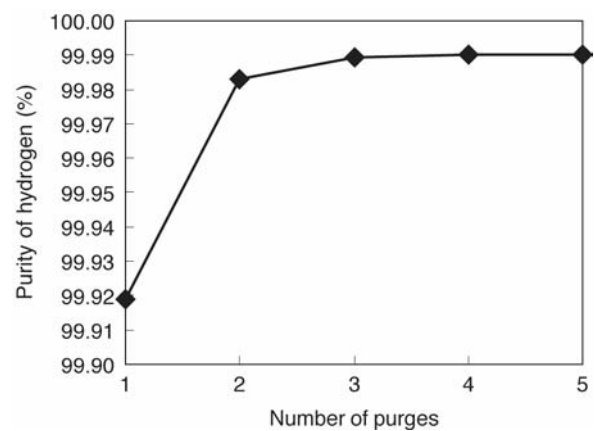


Fig. 9 Purity of hydrogen

In addition, giving due consideration to safety, a flow limiter valve was added to restrict fuel leaks if a pipe disconnects, a pressure relief valve was added to prevent abnormal pressure rise if the pressure regulator fails, and a breakaway device added to prevent fuel leaks if the vehicle moves away. These were added along Plumbing A and B, as shown in Fig. 2.

5. Universal Use

The test apparatus was designed so it was possible to change the height of Plumbing A connecting the hydrogen tanks, as shown in Fig. 2. This made it easy to replace the connectors on the pipe side that connect the pipe to Valve A, which are the tank valves integrated with the hydrogen tanks themselves. Thanks to these measures, it is possible to use, for measurement, hydrogen tanks that are readily available in the USA or in Japan, regardless of their size.

In addition, in order to handle fuel consumption modes that are composed of multiple phases, like the City mode shown in Fig. 10, and so require measurements of fuel consumption for each phase, the number of hydrogen tanks is equal to the number of phases. The hydrogen tanks connected to Plumbing A, as shown in Fig. 2, are placed in a rack, and the tanks can be switched using the B Valves. This arrangement makes it possible to measure fuel consumption for each phase.

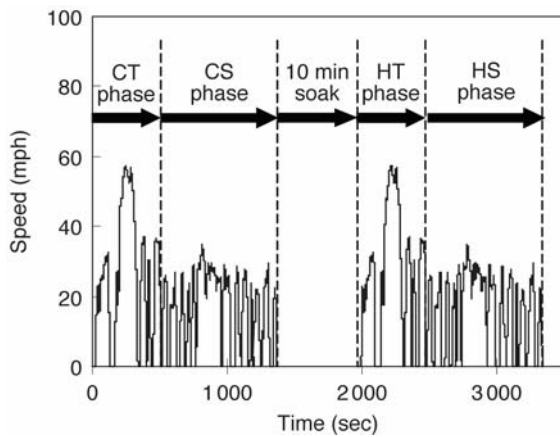


Fig. 10 Phases in CITY mode

6. Cost of Manufacture

Table 1 gives the measurement system specifications. Using readily available parts and avoiding special ones, a simple system was created, that can be manufactured for approximately ¥1.8 million. This has kept the cost to less than that of the carbon balance method used for gasoline vehicles. Figure 11 is a photograph of the measurement system.

Table 1 Measurement system specifications

Type		SUK-1
Dimension	(mm)	W 2000 × D 500 × H 1940
Fuel supply pressure	(MPa)	0.9~1.0
Max. number of tank		6
Safety device		Pressure relief valve
		Flow limiter valve
		Break away device
Manufacture		A&D
Type		GP-30K
Max. mass	(g)	31 000.0
Min. mass	(g)	0.1



Fig. 11 Picture of measurement system

7. Standardization

Keeping in mind automotive emissions regulations, a fuel economy measurement method was required that has a high standard measurement accuracy and reproducibility, particularly for use in the USA. In addition, to be used during the official EPA certification fuel economy test indicated what we think would be one of the test methods applied to other models certified in the USA, and therefore should be one of the standard methods.

EPA and manufactures are now working on the evaluation of measurement methods but according to our evaluation results we believe that weighting method achieved the measurement accuracy and reproducibility required of standard test. As a result, this measurement method and measurement system has been used in 2002 the world's first certification fuel economy test for fuel cell vehicles which was implemented on the Honda FCX. The results of this official test are given in Table 2, and Fig. 12 shows the fuel economy label giving the practical fuel economy values calculated from the test results. All vehicles sold in the USA are required to have the fuel economy label attached, giving the vehicle's practical fuel economy value as recognized by the government. The fuel economy unit used in Table 2 and Fig. 12 is the distance traveled, in miles, for each 1 kg of hydrogen fuel.

Table 2 EPA fuel economy test result for FCX

Mode	Fuel economy (miles/kg Hydrogen)
CITY	56.8
HWY	61.7

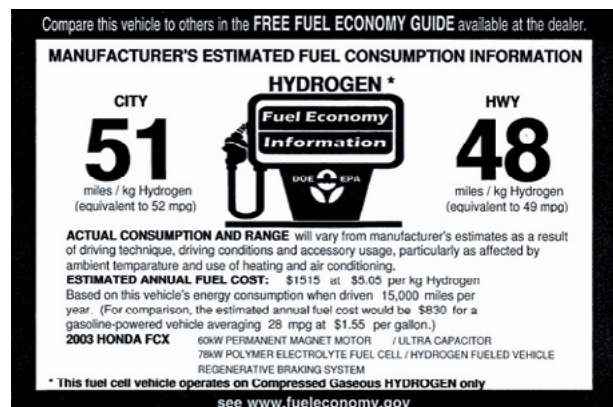


Fig. 12 EPA fuel economy label

8. Summary

By adopting the weight method, reducing measurement deviations, and using the US certification fuel consumption modes, the following results were achieved.

- (1) In both the US fuel consumption certification modes of City and Highway, measurement accuracy of total fuel consumed was 0.286% and 0.125%, so this fully satisfies the SAE standard requiring measurement accuracy of $\pm 1\%$.
- (2) It is possible to create a fuel economy measurement system that can use hydrogen tanks that are readily available not only in Japan but also in the USA. By adding a hydrogen tank switching mechanism, it is also possible to measure fuel economy for each phase.
- (3) The cost of manufacturing the fuel consumption measurement system is approximately ¥1.8 million, which meets the target of no more than ¥2 million. This is a cost lower than that of fuel economy measurement systems using the carbon balance method for gasoline vehicles.
- (4) This measurement method has been used for official fuel economy test method, showing that it can be a standard method.

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