

Development of the Methodology for FCV Post-crash Fuel Leakage Testing Incorporated into SAE J2578

2010-01-0133

Published
04/12/2010

Naoki Kinoshita
Honda R&D Co., Ltd. Automobile R&D Center

Tommy W.L. Chang
American Honda Motor Co., Inc.

Glenn W. Scheffler
GWS Solutions of Tolland, LCC

Copyright © 2010 SAE International

ABSTRACT

This paper explains the new methodology for post-crash fuel leakage testing of Fuel Cell Vehicles (FCVs) and other hydrogen vehicles utilizing compressed hydrogen storage systems. This methodology was incorporated into SAE J2578 that was revised and published in January, 2009.

The new methodology is based on the concept in FMVSS 303 that specifies post-crash fuel leakage test method and criteria for CNG vehicle and adopted some modifications. Specifically, the following items are addressed:

- (1) Allowable leakage can be accurately evaluated in test even with large size tank that obtains only small pressure drop when a given amount of leakage occurs. A new method to deal with the influence of measurement errors was devised.
- (2) Even though only one option of test gas and initial filling pressure is accepted in FMVSS 303, new methodology for hydrogen system allows helium and hydrogen at reduced pressure as alternatives in addition to hydrogen at service pressure. Test with hydrogen at service pressure is easy to perform, but two alternatives are attractive for test safety if leakage occurs during the crash test. Those alternatives are intended to provide results that are equivalent to test with hydrogen at service pressure.

In order to improve the approach used in FMVSS303, a new simulation method was developed that can estimate the pressure change in the storage system after crash based on the mass leakage that could be occurring due to crash damage. Based on this simulation results, approximation equations for calculation of test time and leakage mass criteria were derived including compensations for test gas temperature and initial filling pressure.

The purpose of this paper is to provide the details relative to the simulation procedures and approximation equations used in SAE J2578 as it is envisioned that this approach will serve as the basis for future regulation of allowable post-crash fuel loss in FCVs and hydrogen vehicles.

INTRODUCTION

SAE J2578 "Recommended Practice for General Fuel Cell Vehicle Safety" is one result of comprehensive discussion at SAE Fuel Cell Standards Committee Safety Working Group and is playing a key role in developing international standards/regulations as a leading referenced document. It's also expected to facilitate FCV development moves toward commercially-viable vehicles in the future.

Compared with the specifications in FMVSS 303 for CNG vehicle, the following three modifications are applied for post crash fuel leakage test with hydrogen at service (or nominal working) pressure:

(1) Various kinds of service pressures of hydrogen system can be dealt with. Unlike with CNG vehicle system that has only two close service pressure values of 20MPa and 25MPa, widely apart multiple service pressures need to be considered for FCV system. 35MPa and 70MPa system have already been used and other possible service pressures are also discussed in order to find out optimum approach. To deal with various service pressures, instead of the evaluation with pressure loss as specified in FMVSS 303, evaluation with leakage mass calculated with measured pressure and temperature values is adopted.

(2) To deal with the influence of pressure measurement errors, extended test time is applied for tests with large size tanks. The test time and leakage mass criteria can be calculated with approximation equations that are derived from the results of newly developed leakage simulation.

(3) To ensure accuracy, the influence of test gas temperature and initial filling pressure variation is evaluated and compensation methods are adopted.

REQUIREMENTS IN FMVSS 303

FMVSS 303 requirements are based upon the physical properties of CNG (and nitrogen as a test gas) and pressure measurement errors associated with CNG storage systems of 20MPa service pressure. S5.2 in FMVSS 303 specifies the fuel leakage criteria.

FMVSS 303; S5.2 Fuel system pressure drop: barrier crash

For all vehicles, the pressure drop in the high pressure portion of the fuel system, expressed in kilo Pascals (kPa), in any fixed or moving barrier crash from vehicle impact through the 60 minute period following cessation of motion shall not exceed:

(1) 1062 kPa (154 psi), or

(2) 895 (T/VFS); whichever is higher

where T is the average temperature of the test gas in degrees Kelvin, stabilized to ambient temperature before testing, where average temperature (T) is calculated by measuring ambient temperature at the start of the test time and then every 15 minutes until the test time of 60 minutes is completed; the sum of the ambient temperatures is then divided by five to yield the average temperature (T); and where VFS is the internal volume in liters of the fuel container and the fuel lines up to the first pressure regulator.

APPLICATION OF THE SECOND CRITERION IN FMVSS 303 S5.2

The criterion in FMVSS 303 S5.2 (2) specifies allowable pressure loss due to test gas leakage. Instead of using pressure loss, leakage mass calculated from measured pressure and temperature values is used for evaluation of hydrogen system. The allowable leakage mass from impact through the 60-minute interval at 288K is 606g.

ALLOWABLE LEAKAGE MASS OF HYDROGEN

The criterion stated in FMVSS 303 S5.2 (2) is based on the amount of CNG leakage that is equivalent in combustion energy content to the total amount of gasoline leakage permitted by S5.5 in FMVSS 301. Based on lower heating values of gasoline and hydrogen, allowable hydrogen leakage amount can be calculated.

FMVSS 301; S5.5 Fuel spillage; Barrier crash

Fuel spillage in any fixed or moving barrier crash test shall not exceed 28 g from impact until motion of the vehicle has ceased, and shall not exceed a total of 142g in the 5 minute period following cessation of motion. For the subsequent 25-minute period, fuel spillage during any 1 minute interval shall not exceed 28 g.

According to FMVSS 301, allowable gasoline leakage from impact through the 60-minute interval ends up 1700g as indicated with Eq.1.

Using 42.7 MJ/kg as an average lower heating value for gasoline and diesel fuels described in Table 1, the combustion energy of liquid fuel of 1700g corresponds to 72590kJ. The allowable hydrogen leakage mass in 60-minute interval can be calculated with Eq.2. 119863kJ/kg is the lower heating value of hydrogen. Allowable hydrogen leakage of 606g at 288K of standard temperature in 60-minute interval is the basis for requirements in this methodology.

$$\text{Fuel leakage} = 28\text{g} + 142\text{g} + 28\text{g/min} \times 55\text{min} \approx 1700\text{g} \quad (\text{Eq.1})$$

Table 1. Lower heating values of liquid fuels (adapted from "US DOE Transportation Energy Data Book")

Liquid Fuels	LHV(MJ/kg)
Conventional gasoline	43.438
Reformulated or low-sulfur	42.348
CA reformulated gasoline	42.49
U.S. conventional diesel	42.781
Low-sulfur diesel	42.602

$$m_H = \frac{72590 \text{ kJ}}{119863 \text{ kJ/kg}} = 606g \quad (\text{Eq.2})$$

PRESSURE LOSS DUE TO HYDROGEN LEAKAGE

The following procedures are for the calculation of pressure loss due to 606g hydrogen leakage.

1). Pressure conversion to density

Measured gas pressure is converted to gas density with the approximation equation of Eq.3 that is derived from pressure-density correlation provided in "NIST Chemistry WebBook" (Figure 1). The data ranging from 12MPa to 80MPa is used for making the approximation equation.

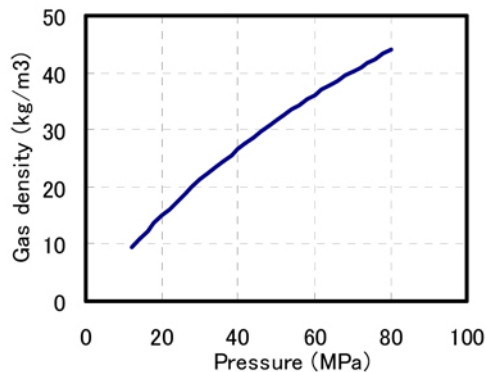


Figure 1. Pressure-density correlation of hydrogen (adapted from "NIST Chemistry WebBook")

$$D_{H2_288} = -0.0027 \times P_{H2_288}^2 + 0.75 \times P_{H2_288} + 1.07 \quad (\text{Eq.3})$$

D_{H2_288} : gas density (kg/m³)

P_{H2_288} : pressure (MPa)

2). Calculation of density drop

The gas density drop due to 606g leakage can be calculated with Eq.4. Gas density values of initial pressure and those after 606g leakage are described in Table 2. The initial pressure values in the top line of Table 2 are assumed as examples of service (or normal working) pressure of hydrogen system.

$$D \text{ (kg/m}^3\text{)} = \frac{606 \text{ (g)}}{\text{Vol (L)}} \quad (\text{Eq.4})$$

D : gas density (kg/m³)

Vol : tank volume (L)

Table 2. Gas density after 606g leakage for each service pressure and tank volume (kg/m³)

Initial pressure		25MPa	35MPa	50MPa	70MPa
Initial density		18.0	23.9	31.6	40.0
After 606g leakage	100L	11.96	17.79	25.53	33.95
	200L	14.99	20.82	28.56	36.98
	400L	16.50	22.34	30.07	38.50
	1000L	17.41	23.24	30.98	39.41

3). Calculation of pressure loss

Gas density values in Table 2 can be converted to pressure values with using Eq.3. Figure 2 shows the calculated pressure loss, the difference between the initial pressure and the pressure after 606g leakage.

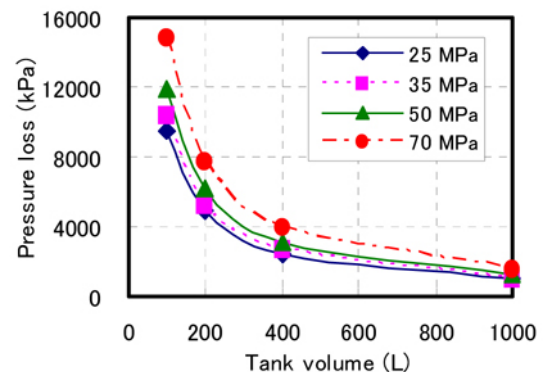


Figure 2. Pressure loss due to 606g leakage (kPa)

Seen from the pressure loss characteristics in Figure 2, it's not practical to make an approximation equation that can calculate pressure loss for various kinds of service pressure and tank volume. Instead of using one equation to calculate allowable pressure loss, which is specified in FMVSS 303 S5.2 (2), leakage mass calculated from pressure and temperature values is used for the evaluation of hydrogen system.

APPLICATION OF THE FIRST CRITERION IN FMVSS 303 S5.2

The criterion in FMVSS 303 S5.2 (1) is based on the consideration for pressure measurement errors. To deal with the errors, extended test time is newly applied for tests with larger size tanks that can expect small pressure loss when 606g leakage occurs. The required extended test time and corresponding leakage mass criteria are calculated with

approximation equations derived from newly developed simulation.

INFLUENCE OF PRESSURE MEASUREMENT ERRORS

The criterion in FMVSS 303 S5.2 (1) is based on the concept that, to ensure accuracy, the total measurement error should not exceed 10% of the value being measured. Since the measurement error for state-of-the-art systems can be estimated about 0.5% of pressure sensor range, the measured pressure loss should be more than about 5% of the sensor range. 1062kPa specified in S5.2 (1) corresponds to 5% of CNG vehicle service pressure of 20MPa. Consequently, the criterion in S5.2 (1) permits excessive leakage for large size tank in case that the pressure loss is less than 1062kPa.

In regard to hydrogen system, Figure 3 shows that pressure loss of more than 5% pressure sensor range can not be accomplished for tanks larger than about 400L when 606g leakage occurs. In this figure, pressure sensor range is assumed to be 1.3 times of service (or normal working) pressure of system. Actually, the leakage mass of 70MPa/1000L tank reaches 1727g when 5% pressure loss occurs, which is about three times of 606g allowable leakage.

In order to adhere to the 5% accuracy requirement and allowable leakage mass of 606g in 60-minute interval, a new test method has been established. The test time of 60-minute period is extended unless a sufficient pressure loss can be expected with 606g leakage.

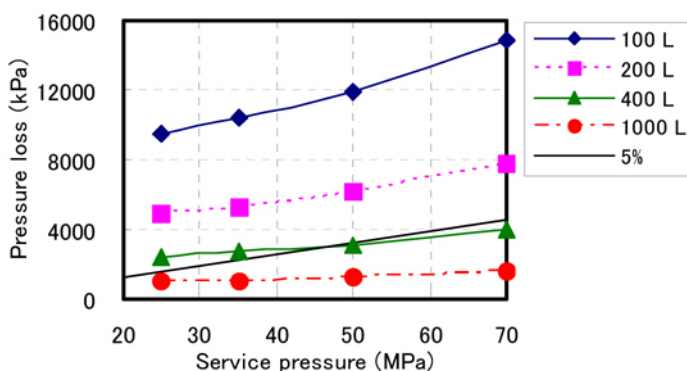


Figure 3. Pressure loss due to 606g leakage (kPa)

DEVELOPMENT OF LEAKAGE SIMULATION

In order to identify the required extended test time, a simulation method that can estimate the pressure and leakage mass characteristics over time has been developed. In J2578, approximation equations derived from simulation results are used to figure out required test time and corresponding leakage mass criteria.

The leakage simulation procedures are composed of two steps, 1) Determination of orifice size and 2) Incremental calculation of pressure and leakage mass.

1). Determination of orifice size

Supposing that hydrogen leakage occurs through an orifice, the orifice area can be calculated based on initial (service) pressure and allowable leakage mass of 606g in 60-minute interval.

At first, it can be assumed that gas flow velocity (F_v) through an orifice is constant while leaking. This assumption is based on the fact that gas flow velocity through choked orifice doesn't exceed a given maximum value. Constant gas flow velocity leads to constant volume loss rate (V_{loss_r}). Constant volume loss rate results in constant gas density loss rate as described in Eq.5 and Eq.6.

$$V_{loss} = F_v \times A \quad (Eq.5)$$

V_{loss} : volume loss per second (m^3/s)

F_v : gas flow velocity (m/s)

A : orifice area (m^2)

$$V_{loss_r} = \frac{Vol - V_{loss}}{Vol} = \frac{M(t+1)}{M(t)} = \frac{D(t+1)}{D(t)} \quad (Eq.6)$$

V_{loss_r} : volume loss rate

Vol : tank volume (m^3)

$M(t)$: mass of gas in tank

$D(t)$: gas density (kg/m^3)

Constant gas density loss rate can be described with the differential equation of Eq.7. Eq.8 is the solution of Eq.7. Eq. 9, the integration of Eq.8, calculates the average gas density in 60-minute interval with substituting values of the initial density and the density after 606g leakage described in Table 2.

$$\frac{D(t+dt)}{D(t)} = C \quad (Eq.7)$$

$D(t)$: gas density at t (kg/m^3)

C : constant number

$$D(t) = D(0) \times \left(\frac{D(1)}{D(0)} \right)^t \quad (\text{Eq.8})$$

$D(0)$: gas density at $t = 0$

$D(1)$: gas density at $t = 1(\text{hr})$

$$D_{ave} = \int_0^1 D(t) dt = \int_0^1 D(0) \times \left(\frac{D(1)}{D(0)} \right)^t dt = \frac{D(1) - D(0)}{\ln \left(\frac{D(1)}{D(0)} \right)} \quad (\text{Eq.9})$$

D_{ave} : average gas density in one hour

When a flow is assumed to be adiabatic, isentropic and with no friction loss, energy conservation law in the flow path is described as [Eq.10](#). [Eq.11](#) that can be derived from [Eq.10](#) is known as the orifice flow equation and available for choked flow (for most gases, a pressure ratio greater than 2).

$$U1 + P1 \cdot V1 + \frac{1}{2} W1^2 = U2 + P2 \cdot V2 + \frac{1}{2} W2^2 \quad (\text{Eq.10})$$

U : specific internal energy (J/kg)

P : pressure (Pa)

V : specific volume (m^3/kg)

W : flow rate (m/s)

$$M = A \times \frac{P}{\sqrt{R \times T}} \times \left(\frac{2k}{k+1} \right)^{\frac{1}{2}} \times \left(\frac{2k}{k+1} \right)^{\frac{1}{k-1}} \quad (\text{Eq.11})$$

M : mass flow rate (kg/s)

A : orifice area (m^2)

R : gas constant (J/kg*K)

P : pressure (Pa)

T : temperature (K)

K : ratio of specific heats

Orifice areas that can release 606g hydrogen in 60-minute interval are calculated with [Eq.11](#) with substituting average mass flow rate of 0.606/3600(kg/s), average pressure values calculated from average gas density of [Eq.9](#), temperature of $T=288(\text{K})$, hydrogen gas constant of $R=4127$ and ratio of specific heats of $k=1.407$. [Table 3](#) shows the results of orifice area calculation. [Figure 4](#) shows the orifice diameters calculated based on the orifice areas in [Table 3](#).

Table 3. Orifice areas for each tank service pressure and volume (/1000 mm²)

	25MP	35MP	50MP	70MP
100L	19.09	12.85	8.67	6.10
200L	16.84	11.73	8.08	5.74
400L	15.93	11.25	7.82	5.57
1000	15.44	10.98	7.67	5.47

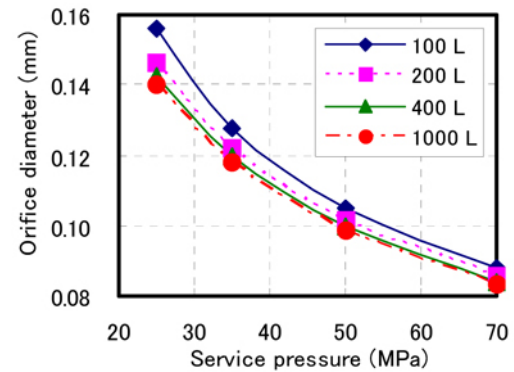


Figure 4. Orifice diameters for each service pressure and volume (mm)

2). Incremental calculation of pressure and leakage mass

Pressure drop and leakage mass characteristics over time can be obtained by incremental calculation of [Eq.11](#). [Figure 5](#) and [Figure 6](#) show the result of leakage simulation with substituting initial pressure of 35MPa and corresponding orifice areas in [Table 3](#). Each tank releases 606g hydrogen in 60-minute interval as described in [Figure 6](#). Detailed procedures and data showing validity of the simulation are described in [appendix A](#).

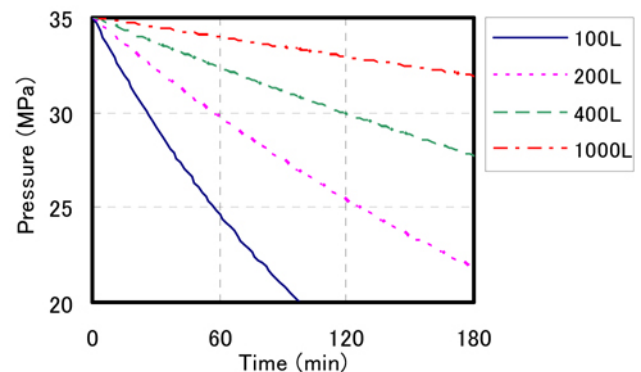


Figure 5. Pressure loss characteristics (35MPa tank)

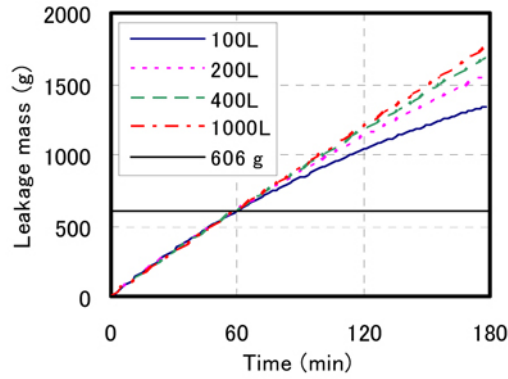


Figure 6. Leakage mass characteristics (35MPa tank)

APPROXIMATION EQUATION FOR CALCULATING TEST TIME FOR 5% PRESSURE LOSS

Figure 7 shows the examples of leakage simulation results of test time for obtaining 5% pressure loss of pressure sensor range. Based on those simulation results, the approximation equation that provides test time (time period to obtain 5% pressure loss of pressure sensor range) can be derived as Eq. 12. The derivation procedures and validity of approximation equation is described in Appendix B.

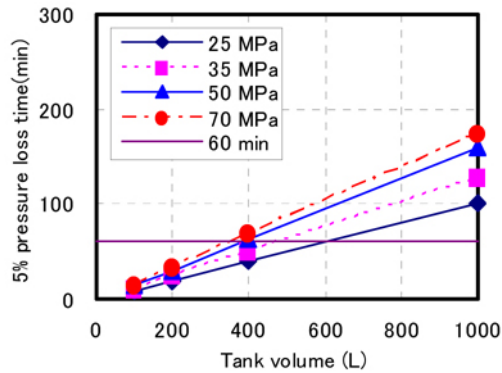


Figure 7. Time for 5% pressure loss ($Rt = 1.3$)

$$Time_{5\%} = \frac{Vol \times SP}{1000} \times \dots$$

$$x((-0.027 \times SP + 4) \times Rt - 0.21) - 1.7 \times Rt, Rt = \frac{SR}{SP} \quad (Eq.12)$$

$Time_{5\%}$: test time for 5% pressure loss (min)

Vol : tank volume (L)

SP : service pressure (MPa)

SR : pressure sensor range (MPa)

Rt : pressure sensor range ratio

CRITERIA OF ALLOWABLE LEAKAGE MASS FOR EXTENDED TEST TIME

Allowable leakage mass of 606g needs to be compensated when an extended test time is applied.

Figure 8 shows the difference of pressure characteristics between large size tank and small one. Compared with 17 minutes of 100L tank, 1000L tank takes 175 minutes to obtain 5% pressure loss. In this figure, 5% pressure sensor range is 4.15MPa with assuming pressure sensor range ratio of 1.3 ($4.15\text{MPa} = 70\text{MPa} \times 1.3 \times 0.05$).

As illustrated in Figure 9, unlike with the 100L tank, leakage mass flow rate for 1000L tank is almost constant till 5% pressure loss is obtained in 175 minutes. Therefore, as described in Eq.13, allowable leakage mass of 606g should be multiplied by the extended test time ratio ($LT/60$) as compensation.

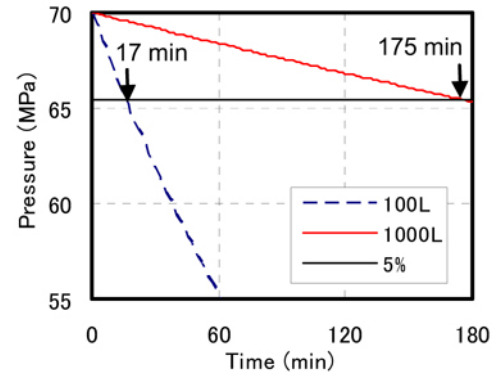


Figure 8. Comparison of pressure characteristics (70MPa tank)