INFLUENCES OF HYDRAULIC SEQUENTIAL TESTS ON THE BURST STRENGTH OF TYPE-4 COMPRESSED-HYDROGEN CONTAINERS

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ABSTRACT

One of the topics for the revision deliberation of GTR13 on hydrogen and fuel cell vehicles is the study of an appropriate initial burst pressure of the containers. The purpose of this study is to investigate the influence of the hydraulic sequential tests on the residual burst pressure in order to examine the appropriate initial burst pressure correlated with the provisions for the residual burst pressure at the End-of-Life (EOL). Specifically, we evaluated any deterioration and variations of burst pressure due to hydraulic sequential tests on 70MPa compressed-hydrogen containers. When the burst pressure after the hydraulic sequential testing (EOL) was compared with the initial burst pressure at the beginning of life (BOL), the pressure proved to have decreased by a few percent while the variation increased. In the burst test it was observed that the rupture originated in the cylindrical part in all the BOL containers while in some of the EOL containers the rupture originated in the dome part. Since the dome part is a section that suffers an impact of vertical drop test, it is conceivable that some sort of damage occurred in the CFRP. Therefore, it was assumed that this damage was the main causal factor for the decrease in the burst pressure and the increase of the burst pressure variation at the dome part.

1.0 INTRODUCTION

The Global Technical Regulation No. 13 (GTR13) [1], which is the global technical regulation on hydrogen and fuel cell vehicles, was adopted at the UN/ECE/WP29 (World Forum for Harmonization of Vehicle Regulations) in June 2013. GTR13 has a basic policy that guarantees the strength of the compressed-hydrogen containers throughout the lifetime by ensuring 180% NWP (Nominal Working Pressure) at the residual burst strength at the End-of-Life of the containers. Following this policy, hydraulic sequential tests have been implemented as a new means. In the hydraulic sequential tests, various tests are continuously performed on a single container, assuming the load applied to the container during its lifetime from the production to the End-of-Life on a vehicle. This sequential tests includes such as the drop test and the ambient temperature pressure cycling test. Each of these tests is almost the same as the test conducted in the conventional standards and regulations (CSA-HGV2 [2], JARI S001 [3], EC79 [4], etc.) of the respective countries. Contrary to the basic policy, the current GTR13 also specifies the minimum burst pressure requirement of 225% NWP for new containers. This requirement has been used under the existing standards and regulations. Nevertheless, a provision for a more appropriate minimum burst pressure is needed from the viewpoint of cost reduction and weight reduction of containers. Therefore, with a view to revision deliberation of GTR13, it is necessary to study the method of how to prescribe an appropriate initial burst pressure in order to ensure the 180% NWP burst pressure at the End-of-Life (for example, abolishing the provisions for the initial burst pressure, reducing it from 225% NWP to 200% NWP, etc.).

This study aims to investigate the influence of the hydraulic sequential tests on the residual burst pressure. Specifically, the hydraulic sequential tests are conducted using 70MPa compressed hydrogen containers to evaluate any deterioration and variations of burst pressure. Finally, suggestions are made for the provision for an appropriate initial burst pressure.

2.0 EXPERIMENT METHOD

2.1 Test container

Compressed-hydrogen containers for motor vehicles from the same lot (continuous production) were used for this study. Table 1 shows the specifications of the containers. The type-4 container has a structure in which a plastic liner is fully wrapped with CFRP (Carbon Fiber Reinforced Plastics). Moreover, in this study, containers designed in accordance with the EC79 regulation that are currently available were used.

Table 1 Specifications of tested Type-4 containers

Nominal working pressure	70 MPa
Volume	36 L
Application criteria	EC79
Liner material	Plastic
Reinforcing material, Molding method	CFRP, Filament winding

2.2 Initial burst test method

To obtain initial (Beginning of life: BOL) burst pressure data, the burst tests for new containers were conducted ten times (Number of tests: n=10). The burst tests were conducted by applying pressure using non-corrosive liquid according to the methods of Burst test (hydraulic) of GTR13. Furthermore, the initial burst test conditions are called BOL-A.

2.3 Hydraulic sequential test method provided for in GTR13

Figure 1 shows the overview of the hydraulic sequential tests of GTR13. In the hydraulic sequential tests, the following tests are conducted sequentially.

(1) Drop test

(2) Surface damage test

(3) Chemical exposure + Ambient temperature pressure cycling test

(4) High temperature static pressure test

(5) Extreme temperature pressure cycling test

(6) Residual strength burst test

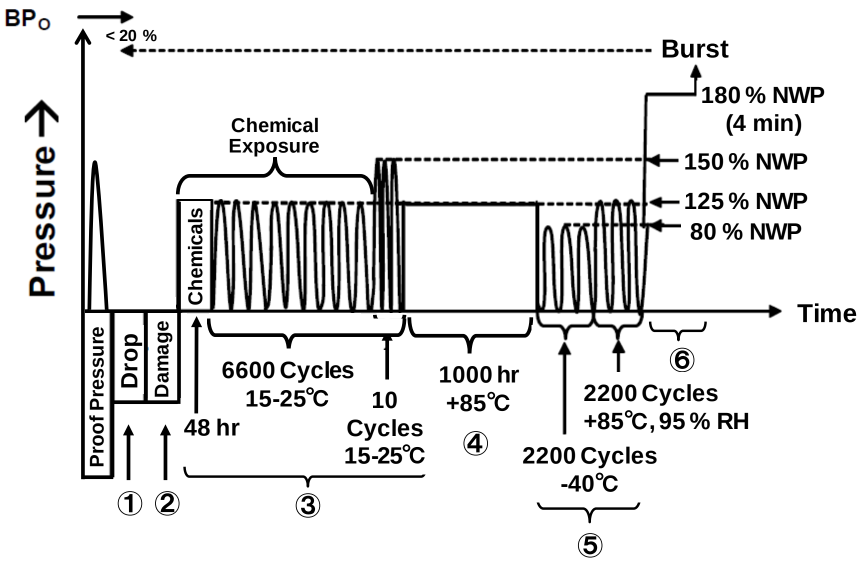


Figure 1 Verification test for performance durability (hydraulic sequential tests)

(1) Figure 2 shows the overview of the drop test. There are different ways to perform the drop test: One way is to drop a single container in three directions and the other way is to drop three containers one direction each. In this study, the tests were conducted in the former method.

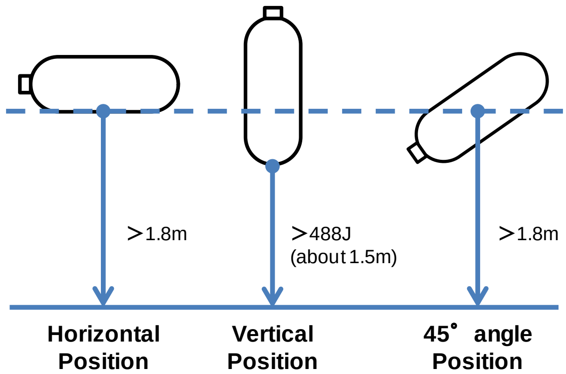
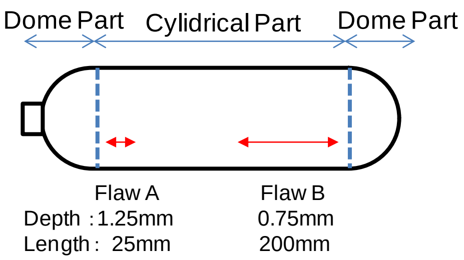


Figure 2 Drop test

(2) The surface damage test includes the surface flaw generation (Figure 3) and the pendulum impacts (Figure 4). In the surface flaw generation, two longitudinal saw cuts were made on the bottom outer surface of the cylindrical part, which are called Flaw A and Flaw B, respectively. The pendulum impacts were made on the five predefined places of the cylindrical part under the same conditions.



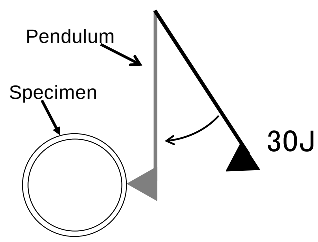


Figure 3 Surface flaw generation Figure 4 Pendulum impacts

The tests enumerated in (3) ~ (5) are tests in which a pressurizing cycle is performed using non-corrosive liquid under the prescribed environment. For the pressure cycling test, an environmental pressure cycling test apparatus consisting of a 120 MPa intensifier and a thermostatic chamber was used. The test was conducted by setting the test container in the thermostatic chamber and regulating the thermostatic chamber to the target temperature and pressuring the container with the intensifier (Figure 5).

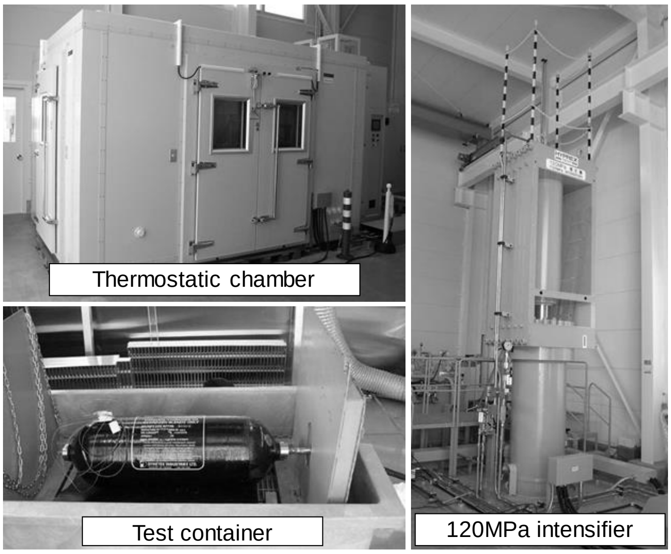


Figure 5 Test apparatus and setting up of test container

(6) The residual strength burst test was conducted using the same method as the initial (BOL) burst test. However, the raising of the pressure was temporarily stopped at 180% NWP, and this pressure level was held for 4 minutes. Then, after checking whether it would burst or not, pressurizing was restarted and the raising of the pressure continued until it burst.

2.4 Examination of End-of-Life test conditions

To conduct the hydraulic sequential tests of GTR13, a long period of about three months is required per container. To obtain data for more than 10 times of tests quickly, test conditions that can substitute the hydraulic sequential test and enable time reduction were examined. Specifically, tests were conducted four times for each of the following three test conditions. By comparing the results, the conditions appropriate for the test to check the residual burst pressure at End-of-Life were selected as the End-of-Life test.

EOL-B: Hydraulic sequential tests of GTR13 (including the burst test)

EOL-C: Test excluding (4) high temperature static pressure test from the hydraulic sequential tests of GTR13 (including the burst test)

EOL-D: Ambient temperature pressure cycling test (11,000 times)＋burst test

3.0 TEST RESULTS

3.1 Initial burst test results

The results of the initial burst test (BOL-A) revealed that the variations of the burst pressure were a little less than 10% (n=10). Moreover, the rupture point was located in the cylindrical part for all the containers.

3.2 Results of examination of End-of-Life test conditions

The burst pressures under the respective conditions (EOL-B, C, D, each n=4) of the End-of-Life test were compared using relative values, assuming that the average value of the results of the initial burst test (BOL-A) was 100% (Figure 6). When the average values were compared, all the burst pressures of the End-of-Life tests showed a decrease of a few % from that of the initial test. Moreover, no difference was observed in the burst pressure due to the difference in the conditions of each End-of-Life test.

Next, the rupture point of each container was examined. In the case of BOL-A (initial), the rupture point was located in the cylindrical part of all the containers. On the other hand, in the case of EOL-B and EOL-C, there were cases where the rupture point was located in the cylindrical part and in the dome part on the end plug side (Figure 7). Also, in the case of EOL-D, the rupture point of all the containers was located in the cylindrical part as with the case of BOL-A. The conclusion was drawn that EOL-D was inappropriate as a substitute test for the hydraulic sequential test because the form of burst was different from that of EOL-B. Since the burst pressures and the forms of burst of EOL-B and EOL-C were the same, EOL-C can be viewed as a substitute test for the hydraulic sequential test. Therefore, it was determined that EOL-B and EOL-C be used as the conditions for the End-of-Life test. Then the EOL-C test with additional 6 pieces of containers was conducted to reduce the time.

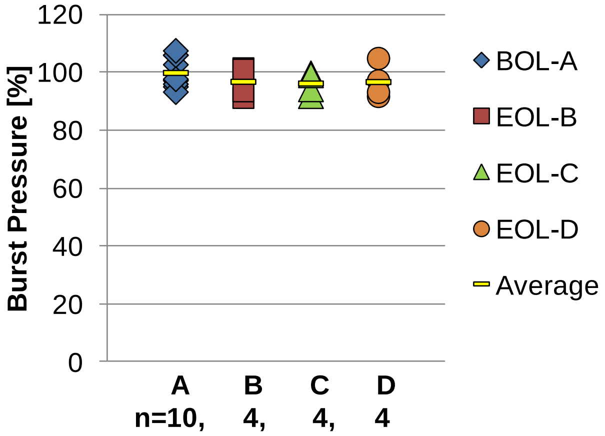


Figure 6 Comparison of EOL test conditions

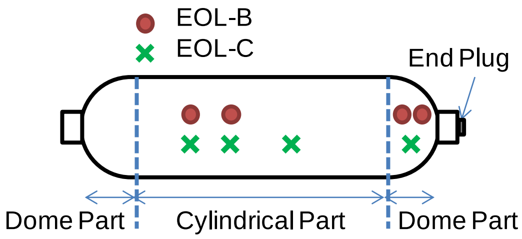


Figure 7 Rupture point of EOL test container

3.3 Initial and End-of-Life burst pressures

The initial burst pressure (BOL-A, n=10) and the End-of-Life burst pressure (total n=14 of EOL-B and EOL-C) were compared (Figure 8). The results revealed that the End-of-Life burst pressure decreased by 5% from the initial burst pressure, based on the average value. Moreover, the variations of the initial burst pressures were a little less than ±10%, whereas the variations of the End-of-Life burst pressures were about +10%/-15% against the average value. The variations were larger on the lower pressure side.

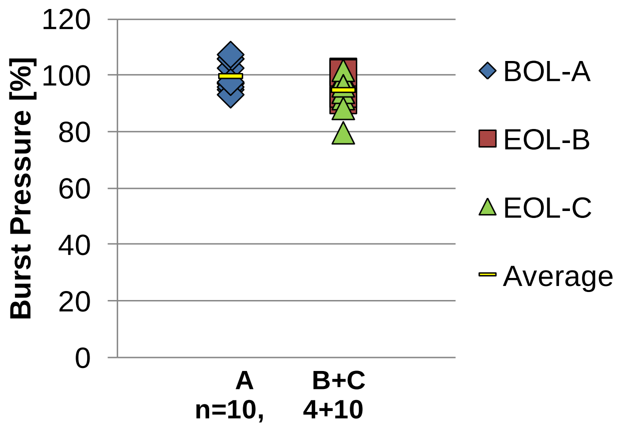


Figure 8 Burst pressure at BOL and EOL

Table 2 shows a sum of the rupture points according to the respective conditions. While the rupture point was located in the cylindrical part of all the containers in the case of BOL-A (initial), the rupture point was located in the cylindrical part for the half of the tests and in the dome part on the end plug side for the remaining half of the tests in the case of EOL-B and EOL-C. Moreover, the dome part on the end plug side is a section that suffers an impact of vertical drop in the drop test. Under all conditions, no containers ruptured from the dome part on the valve side. Furthermore, the burst pressure data of EOL-B and EOL-C were compared according to the location of the rupture point (Figure 9). The variations of the burst pressures were about ±10% when the rupture point was located in the cylindrical part, whereas the variations of the burst pressures were larger on the lower pressure side when the rupture point was located in the dome part.

Table 2 Rupture point

	Cylindrical Part	Dome Part (End Plug side)
BOL-A	10	0
EOL-B	2	2
EOL-C	5	5

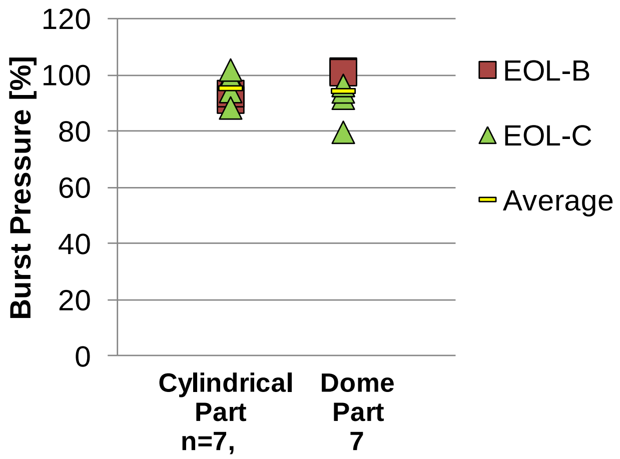


Figure 9 Comparison of burst pressure by rupture point

4.0 DISCUSSION

4.1 Factors for the deterioration of the burst strength

The burst pressure at the End-of-Life decreased by a few percent compared with the initial burst pressure. While the rupture point for the initial (BOL-A) was located in the cylindrical part in all the cases, there were cases where the rupture point was located in the cylindrical part and in the dome part on the end plug side in the case of the End-of-Life tests (EOL-B, C). Since the dome part on the end plug side is a section that suffers an impact of vertical drop test, it is conceivable that some sort of damage occurred in the CFRP by the impact. Therefore, it was assumed that the damage caused by the vertical drop was the main causal factor for the decrease in the burst pressure and the increase of the burst pressure variation in the case of the containers whose rupture point was located in the dome part. Moreover, the decrease in the burst pressure was also observed in the case of the containers whose rupture point was located in the cylindrical part. It is considered that the main factor for this decrease was the surface damage test. In this test, the surface of the CFRP in the cylindrical part was directly damaged by saw cuts and by a pendulum. Therefore, the burst strength in the cylindrical part decreased.

In the ambient temperature pressure cycling test of EOL-D, the average burst pressure decreased by a few % from the initial (BOL-A). However, there is a high possibility of variations because there are containers with a higher burst pressure, compared with EOL-B and C, and the number of tests is small. Moreover, there are reports [5, 6] that the residual strength after completion of the fatigue test of the CFRP test piece and the CFRP container will not decrease. Hence, it is perceived that the effect of the pressure cycling test on the burst pressure is small. In the hydraulic sequential tests0, however, there is a possibility that the degree of the damage to the CFRP caused by the drop test and surface damage test will become larger due to the pressure cycling test.

In addition, the burst pressure and the form of burst were the same when the results of the tests with and without the high temperature static pressure test (EOL-B and EOL-C) are compared. Moreover, there are reports [7] that the CFRP is less likely affected by a long period of the static tensile load. Although these are the results of the evaluation of the stress rapture characteristics at room temperature. It can be said, therefore, that the high temperature static pressure test of the CFRP container is not a factor for the decrease in the burst pressure. Also, a research of the temperature dependency of the stress rapture characteristics will make a more precise validation possible.

4.2 Method of how to prescribe initial burst pressure

In order to optimize the container burst strength, it is necessary to consider how to prescribe an appropriate initial burst pressure. For example, abolishing the provisions for the initial burst pressure, or setting the initial burst pressure to an appropriate value correlated with the provisions of the residual burst pressure at the End-of-Life, etc. In this study, it is considerd the provisions of the minimum initial burst pressure to ensure the 180% NWP at the End-of-Life, based on the investigation results of the decrease in strength and increase in variations by EOL tests.

Assuming that the average value of the initial burst pressure is BP_{BOL} and the average value of the residual burst pressure at the End-of-Life is BP_{EOL}, the obtained data revealed that the initial variations were BP_{BOL}±10%, the variations of EOL were BP_{EOL}+10%/-15%, and the deterioration rate based on a comparison between BP_{BOL} and BP_{EOL} was about 5%. Figure 10 shows the schematic diagram with BP_{BOL} set in such a way that the minimum residual burst pressure at the End-of-Life becomes 180% NWP or more, based on these variations and deterioration rate. From this diagram, it can be understood that if the minimum initial burst pressure is 200% NWP or more, the residual burst pressure of 180% NWP at the End-of-Life will be ensured. Also, from these results, if a new container has a minimum initial burst pressure of 225% NWP, it will have a minimum residual burst pressure of about 200% NWP at the End-of-Life. Hence, it can be said that this is an excessive designing for the requirements of at least 180% NWP at the End-of-Life. These points suggest that it is possible to lower the initial minimum burst pressure from the current prescribed value of 225% NWP to 200% NWP which is correlated with the provisions for the residual burst pressure at the End-of-Life.

However, there is limited data on the deterioration rate and the variations of the burst pressure, since the data were taken from the container of only one type in this study. Therefore, it is necessary to confirm the validity as a general solution by checking containers of other types and those made by other manufacturers. In addition, the containers used this time were designed in accordance with the European EC79 regulation. A more precise validation can be performed by checking containers designed in accordance with the GTR13.

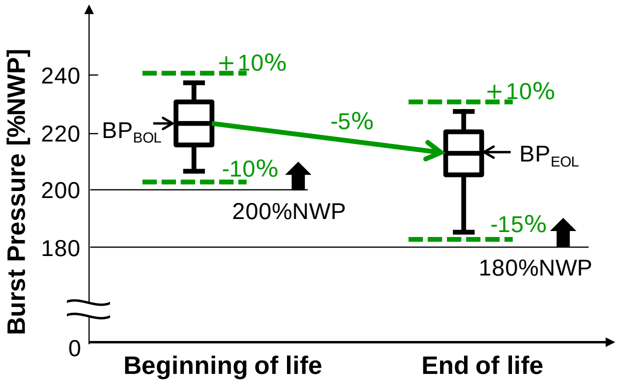


Figure 10 Deterioration of burst pressure between BOL and EOL

5.0 CONCLUSIONS

The hydraulic series tests were conducted using 70MPa compressed hydrogen containers to evaluate any deterioration and variations of the burst pressure. As a result, the following points were recognized.

- The variations of the burst pressure of new containers were a little less than ±10%.
- The residual burst pressure at the End-of-Life decreased by about 5% from the initial burst pressure when the average values were compared.
- The variations of the residual burst pressure at the End-of-Life were +10%/-15% against the average value.
- All the rupture points of new containers were located in the cylindrical part. However, the rupture points of the containers at the End-of-Life were located either in the cylindrical part or in the dome part on the plug side. The cylindrical part is a section that is damaged by the surface damage test. The dome part on the plug side is a section that suffers an impact when dropped vertically in the drop test.

From the results, it is considerd that the drop test and surface damage test are the main factors for the decrease in the burst pressure and increase of the burst pressure variation by the hydraulic sequential test. Moreover, judging from the data about the deterioration and variations of the test container, it is possible to lower the minimum initial burst pressure from the current 225% NWP to 200% NWP which is correlated with the provisions for the residual burst pressure at the End-of-Life.

In the future, in order to clarify the influence of the drop test, research is scheduled to investigate the damage of containers caused by the drop test using the non-destructive inspection. Additionally, research is scheduled to study the influence of pressure cycling on container damage in the drop test.

ACKNOWLEDGMENTS

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