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EXPERIMENTAL STUDY OF HYDROGEN COMBUSTION DURING DCH EVENTS IN TWO DIFFERENT SCALES

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Abstract

Hydrogen combustion tests were performed in two different size facilities to reproduce hydrogen effects during a severe accident with high pressure melt ejection (HPME) and direct containment heating (DCH). The hydrogen was blown out of a pressure vessel into a constrained compartment, modeling the reactor pressure vessel and the reactor pit, respectively, and from there into a large vessel, modeling the containment. A number of distributed igniters simulated hot melt particles. Tests with and without steam and with concentrations of preexisting hydrogen in the containment atmosphere between 0 and 8% were conducted. The paper presents results of two test series with eight and nine tests each.

Introduction

Hydrogen combustion during a severe accident with high pressure melt ejection (HPME) can contribute more than half of the pressure increase in the containment [1, 3, 4]. The most important role plays the time scale of hydrogen combustion [3]. This effect has grown in importance since it was found that pre-existing hydrogen also burns in the same time scale if the concentration in the containment atmosphere is high [1]. The available combustion models are not adequate to reproduce this process and to extrapolate from small scale to reactor scale [2].

Hydrogen is produced in the reactor pit during concurrent melt discharge and steam blow down by oxidation of the metal part of the corium. This reaction can be limited by the amount of available blow down steam or accessible metal. The latter either because of the limited amount of metal in the corium or because the particle sizes are too large to be fully oxidized. Depending on the limiting effects, there is either pure hydrogen flow or mixed hydrogen–steam flow out of the cavity into the neighboring reactor rooms. In these rooms and in the containment dome there is a mixed atmosphere of air, steam and hydrogen, whose composition depends on the accident history. Generally, an elevated pressure due to preceding steam release and a certain hydrogen concentration due to oxidation of fuel rod claddings can be assumed. Hot melt particles serve as igniters and the inflowing hydrogen burns as a flame, while mixing with the oxygen rich atmosphere. The combustion stalls when the oxygen concentration reaches a lower limit or the hydrogen supply ends. In the first case the subsequent hydrogen flows to the next reactor room or the containment dome, where it continues to burn. The release of thermal energy by hydrogen combustion contributes to the containment peak pressure when, firstly, it coincides with the bulk of the heat transfer from dispersed melt particles to the containment atmosphere, and secondly, the heat losses, i.e. heat transfer to structures, are lower than the heat release by combustion.

For an assessment of the effect of hydrogen combustion on the containment load the amount of hydrogen must be known that burns at the DCH time scale. The parameters are (1) the initially existing hydrogen in the containment, (2) the amount of hydrogen produced during blow down and (3) the cavity geometry. Calculations with the dedicated combustion code COM3D [2] revealed that, depending on initial concentration of hydrogen in the containment, three regimes of combustion can be distinguished. In the first regime, which is realized in case of low initial hydrogen concentration, the hydrogen injection will lead to the formation of an attached diffusion flame and the pressure rise in this case is defined by the hydrogen injection rate only. In the second regime the initial hydrogen concentration in the containment is slightly below the lower flammability limit (LFL). The containment atmosphere is not burnable; however an injection even of small amounts of hydrogen can lead to fast formation of large-scale burnable mixtures and thus drastically change the regime of heat release. The rate of heat release in this case is defined by the competition between hydrogen injection, mixing of the injected gas and burnout of the newly formed combustible mixture. After burnout of the volumetric hydrogen a formation of the attached diffusion flame, similar to the first regime, is expected. The third regime is characterized by higher initial hydrogen concentrations. In this regime the initial containment hydrogen concentration is higher than LFL. An ignition of the burnable cloud results in different modes of premixed combustion. The flame speed and connected pressure growth can be different depending on turbulence level, obstruction of the volume, etc. After burnout of the containment hydrogen, again formation of the attached diffusion flame is expected. The code calculations revealed shortcomings of the existing models which made an application of the code for reactor calculations due to the necessary up-scaling unfeasible. Therefore, experiments were performed in two different size facilities having vessel volumes of 14 m^3 and 227 m^3 respectively, corresponding to a scale of 1:18 and 1:7 in regard to large reactor containments. The results can be used to validate code models or directly for extrapolation to reactor scale.

1. Data base of integral tests

The experimental data base consists of integral tests using an iron-alumina melt conducted at Sandia National Laboratories (SNL), Argonne National Laboratories (ANL) and Forschungszentrum Karlsruhe (FZK[1]). The relevant integral tests are the SNL/IET series with Zion and Surry geometries (Westinghouse) in scale 1:10 and 1:6, respectively [4,5,6], the ANL/IET series with Zion geometry in scale 1:40 [7,8], a set of two tests with a geometry similar to a Combustion Engineering Plant and the EPR in scale 1:10 [9], the FZK/DISCO-H series with EPR geometry in scale 1:18 [10] and the FZK/DISCO-FH series with the geometry of the French 1300 MWe plant P’4 in scale 1:16 [11].

Westinghouse Reactor Geometry (Figure 1 a)
An analysis and summary of the findings from IET-experiments (Integral Effects Tests) regarding the hydrogen effect was given by M. Pilch [3, 4]. The hydrogen combustion contributed significantly to containment pressurization. The peak pressure increase in tests with a non-reactive atmosphere was 0.1 MPa, while in an air-steam atmosphere it was between 0.25 and 0.3 MPa, regardless of the presence of 2 to 3 % preexisting hydrogen or none. Some of the preexisting hydrogen burned, but this had only a minor impact on the peak pressure. The DCH efficiency was 0.46 ± 0.02 for five tests [4]. It was lower, 0.28 – 0.35, for tests with either no hydrogen combustion (IET-1 and IET-1R) or test with preexisting hydrogen (IET-6 and IET-7). In one case

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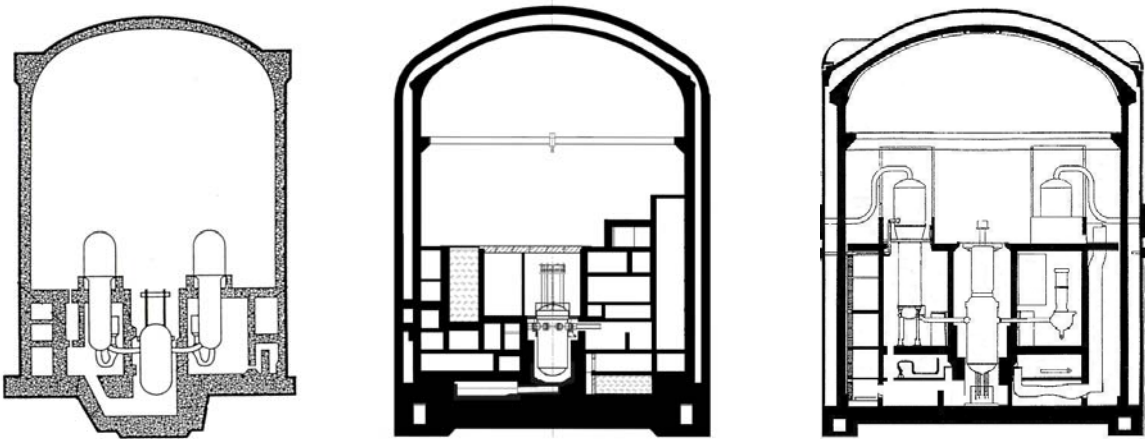

a **b** **c**

Figure 1 Schematic of tested reactor building designs

(IET-11) most (95 %) of the available hydrogen burned, including the preexisting hydrogen inventory. Here, the DCH efficiency was also 0.46, which means that a larger part of the hydrogen did not burn at DCH time scale and/or heat transfer to cold structures at the same time scale mitigated the pressure increase. The pressure peak was reached at 3 seconds (linear scale 1:6). The tests indicated that diffusion flames did not occur when the oxygen concentration drops below about 5 – 8 %. Hydrogen combustion, and correspondingly, peak containment pressures decreased with increasing steam concentrations and decreasing oxygen concentrations. During the accident, the oxygen concentration is reduced either by metal oxidation and hydrogen burning or addition of steam.

Combustion Engineering and EPR Geometry (Figure 1 b)
The two tests conducted in the Surtsey facility (scale 1:10) with a geometry similar to a Combustion Engineering Plant and the EPR were characterized by the direct open path from the reactor pit to the containment dome – different to EPR geometry – and a low primary pressure (1.1 and 1.5 MPa), which means a small amount of blow down steam [9]. The containment atmosphere was a mixture of 46 % steam, 40 % nitrogen, 11 % oxygen (equivalent to air) and 3 % hydrogen (corresponds to 360 kg in full scale). The breach diameters related to 1.0 m and 0.4 m, respectively.

The striking result was the large hydrogen production equivalent to 7 % of the containment atmosphere in the first test and 5 % in the second. This is about 6 times as much as what could have been produced by the reaction with the blow down steam. These large amounts can only be realized by oxidizing airborne melt particles by atmospheric steam in the containment. A reaction with oxygen in the containment atmosphere without hydrogen production is also possible and cannot be distinguished from that with steam by post-test gas analysis. The analysis showed further, that 90%, respectively 75 % of the total available hydrogen was burned.

The peak pressure increase in these two tests was 0.4 MPa for the test with the large breach and 0.2 MPa for the small one. The pressure increase by hydrogen combustion alone would amount to 0.6 MPa and 0.4 MPa, respectively, if all energy was released within DCH time scale of 3 seconds and no heat losses occurred. The contribution to pressure increase by thermal energy from the dispersed melt is 0.2 and 0.1 MPa, respectively. This DCH efficiency of 50 %, respectively 40 %, is evidence for a slow volumetric combustion lasting much longer than the steam blow down. In the experiments combustion was observed in the containment dome region by video long after the melt had settled on the operating deck.

In the DISCO facility the H-series of experiments was performed with similar geometry and conditions as the two tests in the Surtsey facility, but at a scale 1:18 instead of 1:10. However, in some tests the direct flow path into the containment was closed, as realized in the final EPR design [10]. The initial hydrogen concentration in the containment was around 3 %. Similar to the Surtsey test #1 with an open flow path and large breach, the amount of hydrogen produced during blow down of steam and melt was twice the amount of the preexisting one. In the other tests with a closed flow path or smaller breach the amount of hydrogen produced was only little larger than initially present. Of the total available hydrogen 83 %, respectively 66 % burnt for the two open pit cases, and 48 ± 5 % for the closed pit cases. However, the DCH efficiency was only 34 ± 4 % for all cases. The containment peak pressure was generally reached at 1.75 seconds, while flames were observed up to 6 seconds after breach opening. This confirms the low efficiency of hydrogen combustion. Peak pressure increases of 0.24 MPa with open pit and 0.1 MPa with closed pit were measured.

The French 1300 MWe Reactor P'4 (Figure 1 c)
The cavity of the P'4 plant has a direct flow path into the containment dome [11]. Three out of four tests with a reactive atmosphere had a relatively high preexisting hydrogen concentration between 5 and 6 %. The hydrogen production was not affected by this, but a higher fraction burned, i.e. 78 ± 5 % vs. 36 % in case of less preexisting hydrogen. Also with the high concentration, the peak pressure was reached earlier and the DCH efficiency was higher with an average of 54 % vs. 40%. A large part of the preexisting hydrogen was burned during the blow down process. Consequently, the containment loads were higher too, with peak pressure increases between 0.3 and 0.35 MPa, while the pressure increase was only 0.1 MPa with low initial hydrogen concentration.

2. Separate effects tests

2.1 Test facilities

The schemes of the two test facilities are shown in Figure 2 in similar scale. Three main components of a reactor, respectively their volumes were modelled, the reactor pressure vessel (RPV) including the volume of the primary cooling system (RCS), the reactor pit and the containment. No compartments were modelled in the basic experiments. These were modelled for two complementary tests in the small facility. The main dimensions, flow areas and volumes of the two facilities are given in Figures 2 and 3 and in Table 1. The opening mechanism in the exit tube located at the bottom of the RPV vessel was different in the two facilities. In the small facility it was a ball valve, which had opening times between 68 ms and 192 ms. In the large facility it was a rupture disk, which was fully open within less than 5 ms.

To simulate the melt droplets, which serve as fuses in a real case, thermite igniters, so-called sparklers, were placed at each of the four cavity exit pipes and eight other locations at different levels in the containment. They are started by electric resistance heating 1.2 seconds before initiating the blow down. They can ignite a hydrogen-air mixture in a radius of approximately 5 cm. They furnish sparks for a period of approximately 10 seconds.

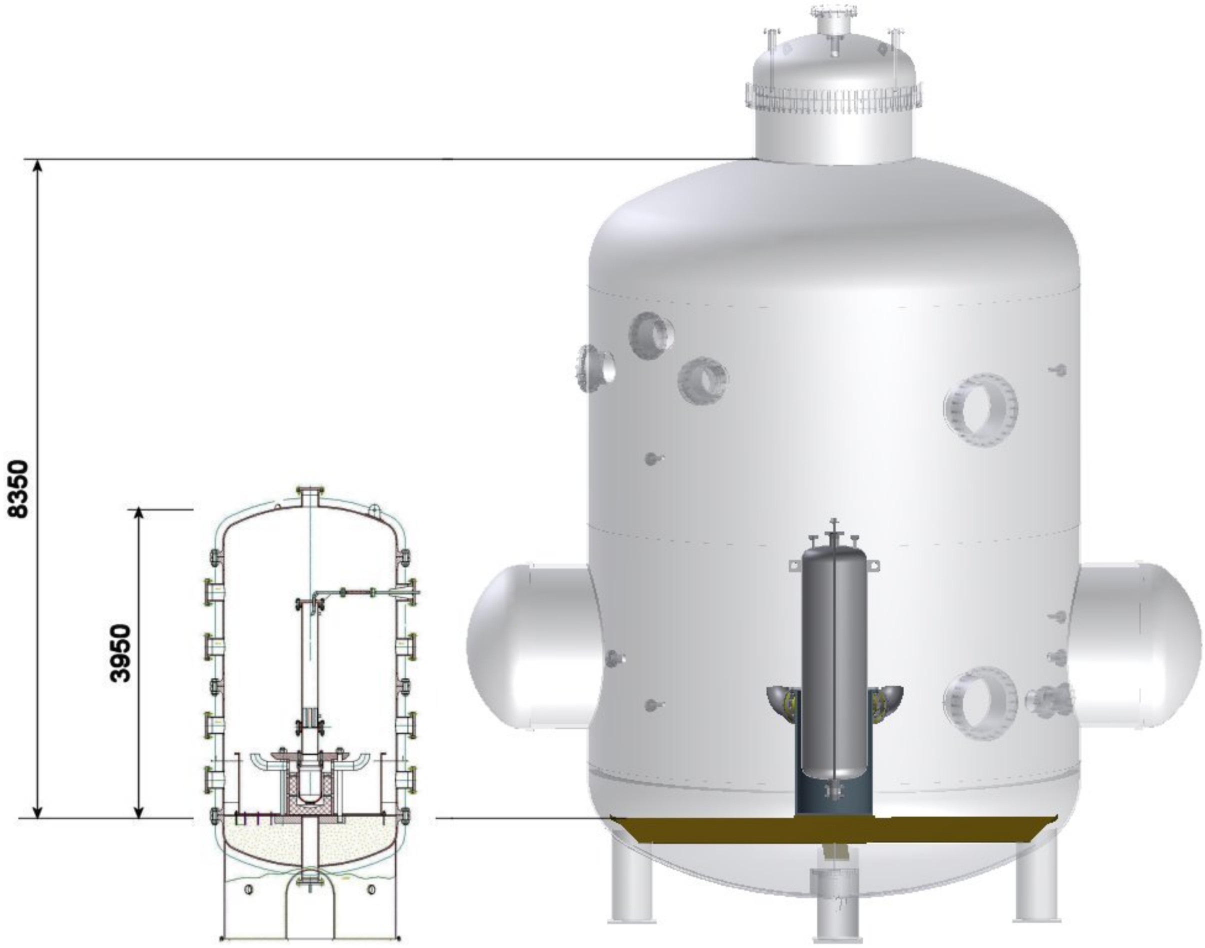

Figure 2 The two test facilities in scale.

Table 1: Geometric parameters of the Small and Large test facility

		Small	Large
Containment vessel diameter (inner)	m	2.170	5.948
Containment total freeboard volume	m³	13.88	221.1
RCS and RPV total volume	m³	0.0801	1.278
Pit flow area of annulus (minimum flow cross section)	m²	0.0212	0.141
Pit flow area in upper part of cavity	m²	0.1583	0.141
Pit total flow area at nozzles (pit to containment)	m²	0.0232	0.145
Pit flow cross section of 4 connecting pipes	m²	0.0346	0.234
Pit empty volume (without RPV)	m³	0.0748	0.969
Pit free volume	m³	0.0365	0.378
RPV exit tube length	m	0.258	0.243
RPV exit hole / tube diameter	m	0.025	0.0625
RPV exit hole area	m²	0.000491	0.00307

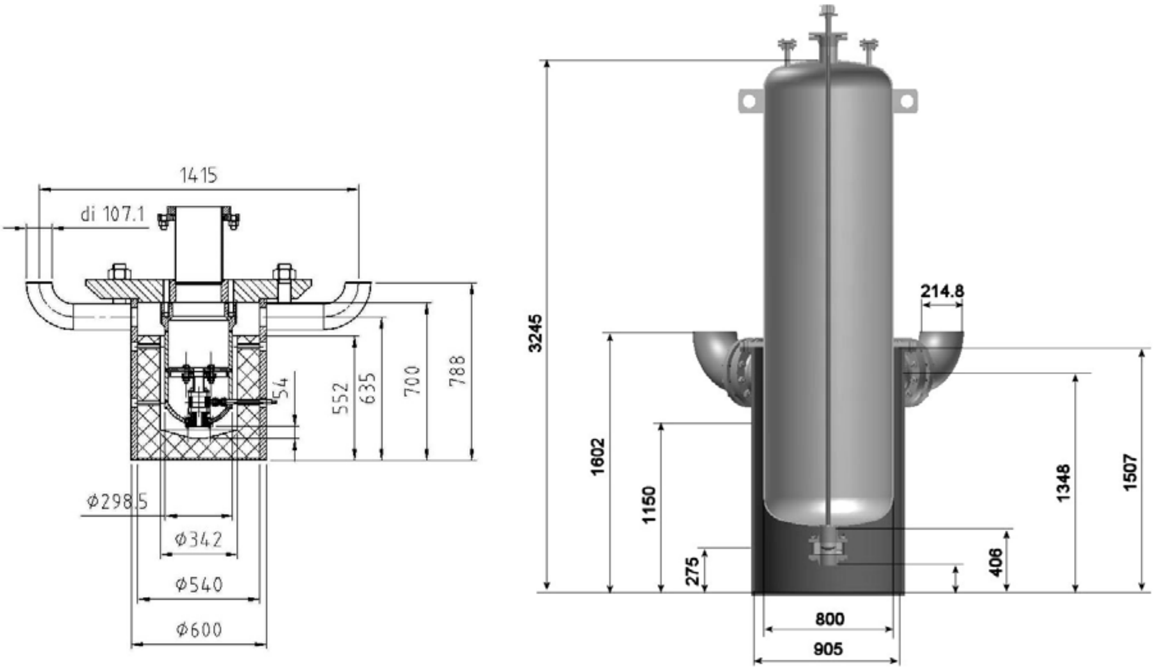

Figure 3 Dimensions of the RPV/RCS vessels and the reactor pits (in mm).

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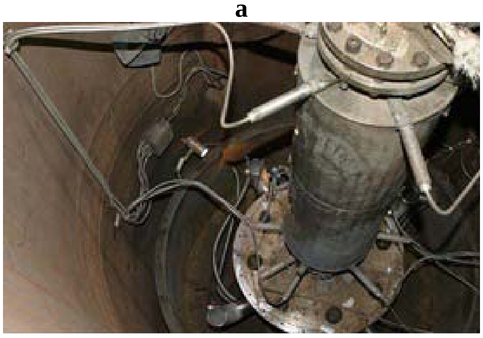

b

c

Figure 4 a. View into containment vessel and open pit of small facility; b. same view with RCS/RPV vessel installed; c. view of RCS/RPV and pit of large facility.

2.2 Instrumentation and conduct of the experiments

2.2.1 Small test facility (G0 test series)

Ten K-type thermocouples, with an outer diameter of 0.36 mm, are placed at different locations in the containment vessel to measure the gas temperature. A total of 14 strain gauge-type pressure transducers (12 Kulite® and 2 Kistler®) measure the transient pressures in the RCS/RPV pressure vessel, the cavity and the containment. The Kistler transducers were mounted outside the facility in cold environment connected with a pipe to the measurement position. They were used as reference for the Kulite transducers during stationary periods of the experiment. Four video cameras providing 50 frames per second were used. Two cameras were looking down from the top cover, one had a horizontal view from a second level port, and one used an endoscope introduced in a first level port. Nine pre-evacuated gas grab sample bottles are used to collect dry-basis gas samples at three different heights in the containment. The sample lines and the sample bottles are at room temperature, thus the bottles are being filled with non-condensable gases (nitrogen, oxygen, hydrogen, carbon dioxide and monoxide) and steam that condenses. One pretest sample collects background information just prior to the start of the blowdown. One sample at all three stations each is taken 10 seconds and one 5 minutes after the blowdown. The amount of hydrogen, that is produced and burned during the test, can be determined by the nitrogen ratio method [1], [5], [12].

The containment vessel is heated over a time period of approximately 12 hours by filling with steam additional to the atmospheric air until the vessel pressure reaches 0.2 MPa. The condensate water is drained at the bottom of the vessel from time to time. The average gas temperature and the wall temperature inside the vessel is 373 K (100°C) at the end of the heat-up. A metered amount of hydrogen gas is added to the vessel at the end of heat-up while fans are running inside the vessel. Then the RCS/RPV vessel is filled with the projected amount of hydrogen, the fans are stopped and the experiment is ready to start by initiating the computer controlled sequence. If a mixture of steam and hydrogen is foreseen as blowdown gas, steam is filled into the RCS/RPV vessel by opening a valve in the line connected to a steam accumulator placed outside the containment vessel for the period of one second. Then the sparklers are ignited and after one second the ball valve is opened to start the blowdown.

2.2.2 Large test facility (GL-test series)

The instrumentation and experimental procedure was kept similar as much as possible to those in the small test facility. One K-type thermocouple was inside the RPV vessel and 23 thermocouples were placed inside the containment vessel at four levels. A total of 9 strain gauge-type pressure transducers (7 Kulite® and 2 Kistler®) were used to measure gas pressure in the three vessels. Twelve thermite igniters were placed inside the containment similar as to the small facility. Pre-and post-test gas analysis was done as in the small test facility with twelve pre-evacuated gas sample bottles in a well-mixed atmosphere.

To shorten the necessary time for heating the containment atmosphere by steam, the air inside the vessel was heated by an electric heater before steam was filled in. The other difference in procedures was the fact that no tests with steam blow-down were done. The gas in the RPV/RCS vessel was always hydrogen with varying amounts of nitrogen. After the igniters have been started the blow-down is initiated by punching the rupture disks with a steel bullet.

2.3 Test parameters

Table 2: Initial conditions and results of tests in the small facility

		G01	G02	G03	G04	G05	G06	G07	G08
RPV pressure	MPa	2.0	2.0	2.0	1.9	2.0	2.2	2.7	2.0
Steam concentration in cont.	mol %	0	0	0	37.7	33.4	38.6	35.2	36.2
H_2 concentration in cont.	mol %	0	0	2.2	2.6	7.0	5.0	6.0	2.7
Initial H_2 in containment	mol	0	0	25	23	64	49	55	25
RPV-blow down H_2	mol	44	49	24	25	26	51	53	26
Total available H_2	mol	44	49	49	48	90	100	108	51
Burned H_2 (N_H)	mol	44	36	27	30	81	74	72	24
Fraction burned	-	1.0	0.73	0.55	0.58	0.86	0.78	0.67	0.46
H_2 post-test concentration	mol %	0	1.2	1.9	2.2	1.1	1.7	3.6	2.9
Measured peak pressure increase	MPa	0.14	0.13	0.11	0.11	0.27	0.23	0.25	0.09
Theor. maximum Δp_{theo}	MPa	0.30	0.25	0.16	0.18	0.50	0.46	0.44	0.15
Efficiency $\Delta p_{exp}/\Delta p_{theo}$	-	0.46	0.52	0.67	0.60	0.54	0.50	0.56	0.61

Table 3: Initial conditions and results of tests in the large facility

		GL1	GL2	GL3	GL4	GL5	GL6	GL7	GL8	GL9
RPV pressure	MPa	1.8	1.8	1.8	1.8	1.8	1.8	-	1.8	1.8
Steam concentration cont.	mol %	0	0	0	32.0	33.2	48.3	0	0	46.4
H_2 concentration in cont.	mol %	0	2.8	2.3	3.1	6.8	5.9	7.8	5.4	5.9
Initial H_2 in containment	mol	0	403	347	352	797	741	1198	795	710
RPV-blow down H_2	mol	671	602	338	327	343	*650*	-	351	*610*
Total available H_2	mol	671	1005	692	679	1140	1391	1198	1146	1320
Burned H_2 (N_H)	mol	657	916	394	409	870	1059	1037	872	1031
Fraction burned	-	0.97	0.91	0.57	0.60	0.76	0.76	0.87	0.76	0.78
H_2 post-test concentration	mol %	<0.1	1.7	1.9	2.2	2.2	3.2	0.8	2.1	3.1
Measured peak pressure increase Δp_{exp}	MPa	0.13	0.15	0.10	0.11	0.18	0.17	0.32	0.20	0.16
Theo. maximum Δp_{theo}	MPa	0.25	0.34	0.15	0.15	0.33	0.40	0.39	0.33	0.39
Efficiency $\Delta p_{exp}/\Delta p_{theo}$	-	0.53	0.43	0.71	0.71	0.56	0.44	0.83	0.60	0.42

The most important initial conditions for both test series are listed in the upper parts of Table 2 and Table 3. The complete data can be found in the reports [12] and [13]. In the small facility tests G01 through G06 were done in the simplified geometry (Fig. 2) while a more prototypic geometry containing a subcompartment was applied in tests G07 and G08. The pre-existing hydrogen concentration in the containment vessel was varied between 0 and 7 %, and the hydrogen mass blown into the containment was varied by the same amount. Containment atmospheres without and with steam were applied.

Nine tests were performed in the large facility. The initial pressure in the RPV was 1.8 MPa, while the containment pressure was between 0.16 and 0.22 MPa. Four tests were performed in a dry containment atmosphere, without steam (GL1, GL2, GL3, GL8). In these four tests the hydrogen concentration in the containment was varied between 0 and 5.4%, and a similar amount of hydrogen was stored in the RPV, together with nitrogen to obtain the pressure of 1.8 MPa. Also, four tests were conducted with a wet containment atmosphere, approximately 0.1 MPa air and 0.1 MPa steam (GL4, GL5, GL6 GL9). Here the hydrogen concentration varied between 3.1 and 6.8%. Finally one very basic test was conducted (GL7), in a dry containment atmosphere with a high hydrogen concentration above the flammability limit (7.8%), without blow-down of hydrogen.

2.4 Results

Figures 5 and 6 show the pressure increase in the containment for the two test series, all data shifted to the same initial containment pressure of 0.2 MPa. In the small scale tests the containment peak pressures are reached generally after 1 second (time for prototypic scale would be 18 seconds). Only the hydrogen which burns during the first short period of time contributes to the pressure increase. However, flames could be observed in the tests also at later time, when the pressure decreased again. In test G05, having the highest hydrogen concentration of 7% in the containment, the hydrogen began to burn when the igniters started 2 seconds before blowdown commenced. The results regarding the height of the peak pressure in the containment fall into two groups. Tests G05, G06 and G07 with total hydrogen amounts close to 100 moles, and the other tests with amounts of 50 mol.

In the large scale test series two tests with similar total hydrogen masses (GL2 and GL8) show different pressure increases. In GL2 the pre-existing hydrogen concentration in the containment was low and a large mass of hydrogen was blown down, resulting in a lower pressure increase (0.15 MPa) compared to test GL8 (0.20 MPa), where the conditions were vice versa. In tests GL3 and GL4 similar amounts of hydrogen were involved in both, RPV and containment. While test GL3 had a dry atmosphere test GL4 had a wet atmosphere. However, the pressure increase is the same in both cases, which means there is no effect of steam in the atmosphere. The most striking curve is that of the simple hydrogen combustion in the dry atmosphere (GL7). Here a pressure rise of more than 0.3 MPa is obtained. The total hydrogen mass was similar as in test GL6, but all well mixed in the containment at time of ignition, thus the combustion was fast and efficient. Test GL5 had the highest concentration before blow-down (except in GL7), but it was already above the ignition limit. So, hydrogen started to burn, when the igniters were started. The pressure decreased already, when the blow-down commenced. Consequently, the pressure increase was relatively low.

A comparison of some tests in small scale with similar tests in large scale is shown in Figure 7. The time is scaled to prototype scale, i.e. multiplied by a factor of 18 for the G0 series and 7 for the GL series (linear length scale). GL1 and G02 are tests of blow-down in a dry atmosphere without pre-existing hydrogen, basically simple hydrogen torches. The peak pressures are identical. GL3 and G03 are both tests in a dry atmosphere with small pre-existing and small blow-down hydrogen masses, which show a small difference in the peak pressure, but this is within the experimental uncertainty in initial conditions. GL4 and G04 are the corresponding tests in a wet atmosphere; again identical pressure increase is found also at the same time. There are no exactly matching tests with high hydrogen masses, which can be compared directly (as G06 with GL6); but taking into account the differences, the resulting peak pressures are similar again. In prototype scale the peak pressures would be reached about 16 to 25 seconds after blowdown commenced. Also the decline of the pressure is similar in both scales, which means that the heat losses are similar in magnitude and time scaling, although different for different conditions.

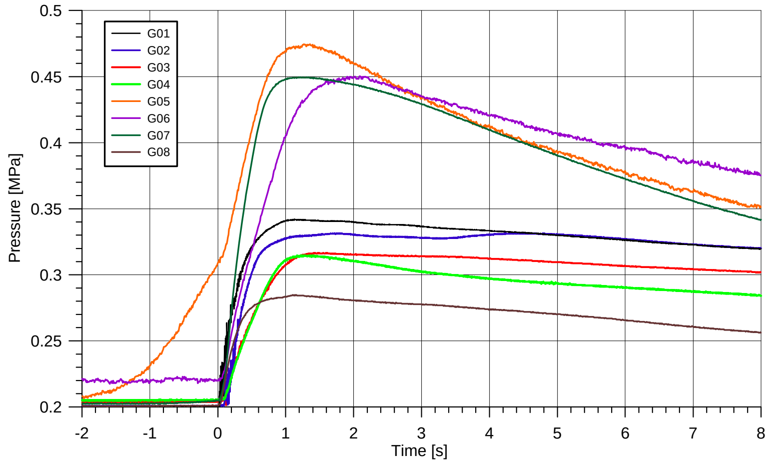

Figure 5 Containment pressure curves of the small scale test series.

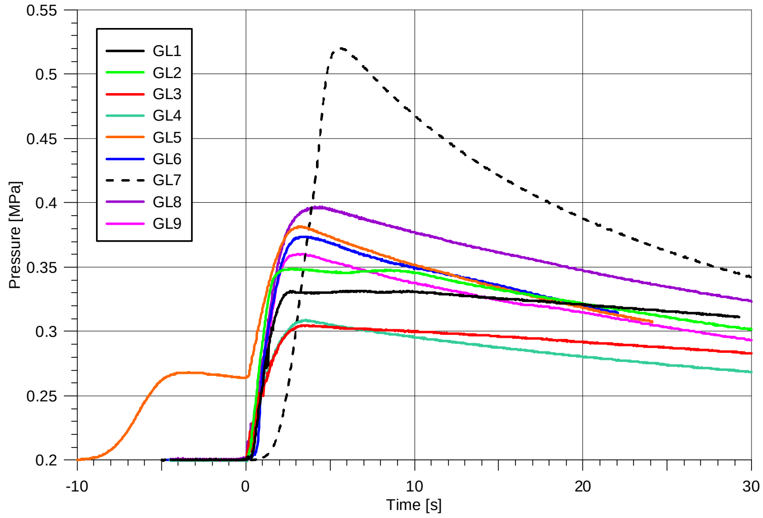

Figure 6 Containment pressure curves of the large scale test series.

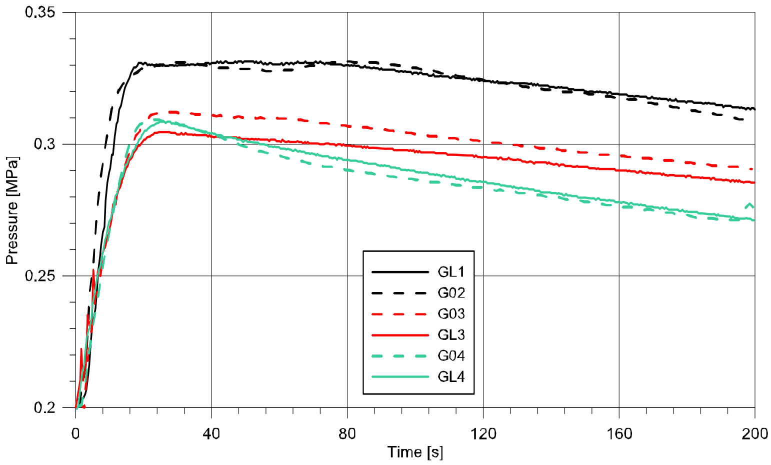

Figure 7 Comparison of pressure curves from small and large scale tests with similar initial conditions, time axis scaled to prototype size (1:1).

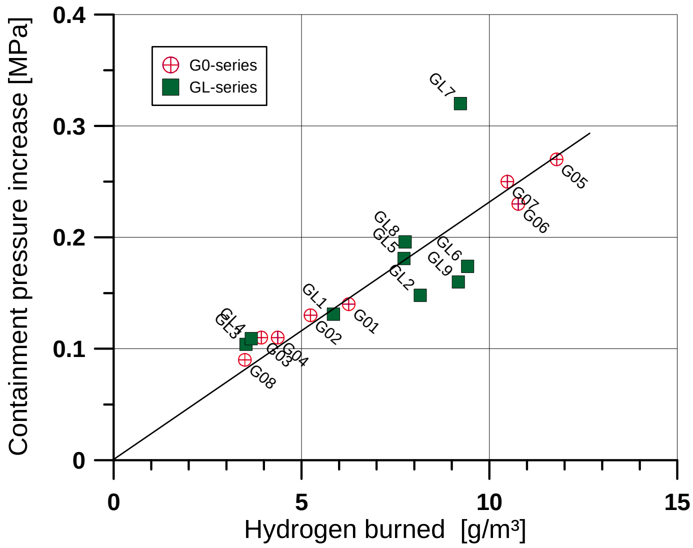

Figure 8 Pressure increase versus burned hydrogen.

From the pre- and post-test gas analysis the amount of hydrogen that burnt was determined. The data of three, respectively four measurement stations were averaged. The uncertainty of these results is in the order of 5%. The data are listed in Table 2 and 3. Figure 8 shows the pressure increase in the containment vessel over the amount of hydrogen burnt during the entire duration of the test reduced by the containment volume. The pressure increases linearly with the amount of burned hydrogen, with little scatter and neither a scaling effect nor an effect of wet or dry atmosphere. The non-matching test GL7 was the test without blow-down, simple multi-ignited hydrogen combustion. The relation between the amount of burnt hydrogen and the total available (*fraction burnt* in Tables), respectively the pre-existing or the blow-down hydrogen must be studied in detail and is not so simple. If there is only blow-down hydrogen (as in G01, G02 and GL1), the fraction which burns is very high; in case of G01, which had a very large blow-down diameter (nozzle), it is even 100%. It is still high if the amount of blow-down hydrogen is higher than the pre-existing amount, as in GL2. Apart from this, the general trend seems to be: the higher the total amount of hydrogen, the higher the fraction which burns.

The theoretical possible pressure rise resulting from the energy release by hydrogen combustion can be approximated by combining the caloric equation of state with the ideal gas law, $\Delta p = \Delta Q(\kappa-1)/V$, with κ the ratio of gas specific heats and V the containment volume. The energy release by combustion is $\Delta Q = \Delta q\ N_H$, with Δq = 242 kJ/mol burnt H_2 and N_H burnt hydrogen moles. The ratio of measured to theoretical pressure increase is the efficiency of the process, a measure for all heat losses involved. The efficiency lies between 42 and 71%, excluding the combustion without blow-down (GL7); the average efficiency is 55%.

3. Conclusion

Hydrogen combustion tests at DCH conditions conducted in two different size facilities have shown that there is no scaling effect relative to the pressure increase in the containment and the times of peak pressure scale exactly with the length scale. The pressure increase correlates with total hydrogen burned. The fraction of hydrogen that burns depends on the ratio of pre-existing to blow-down hydrogen and on the total amount of hydrogen and varies between 46% and 100%. Compartments may have an effect on the burnt fraction but this has not been investigated in depth. The efficiency of combustion energy conversion into pressure varies between 42 and 71% and again may be affected by compartments and structures in the containment. These effects can be analysed by code calculations, for which the experimental results may serve as a data base for code modelling and validation.

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