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Large scale hydrogen-air combustion experiments with dynamic H_2-injection and spark ignition

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ABSTRACT: Experiments with dynamic H_2-injection into air have been performed to investigate the consequences of deliberate ignition under dynamic initial conditions. A wide spectrum of combustion processes was observed ranging from very slow deflagrations to stable detonations. Hydrogen mixing occurs mainly during jet flow dissipation by turbulent entrainment of air. Ignition occurs only after arrival of the well mixed H_2-air cloud at the ignitor position. The resulting combustion mode is governed by the H_2-inventory of the cloud at the time of ignition and by its scale. The experimentally determined DDT limit was used to derive a relation between the properties of the H_2-source, of the compartment, and of the ignitor (location, spark frequency), necessary to avoid DDT events. The new results provide guidelines on how to optimize an ignitor system for the local conditions in a given compartment of a reactor containment.

1. INTRODUCTION

Deliberate ignition of combustible mixtures is a potential hydrogen mitigation technique for severe accidents in PWR's with large dry containments (e.g. Heck, 1992). The basic idea is to start a burn at the earliest possible time. If successful, the large amounts of hydrogen which can potentially develop during a severe accident are burned in multiple, but small combustion events, without generating significant containment loads.

This concept has been tested extensively for homogeneously premixed, quiescent and isothermal initial conditions, for lean mixtures and empty test rooms (e.g. Kanzleiter, 1992; PHDR, 1994). These conditions are more representative for containment regions located far away from the H_2/steam release point, e.g. the containment dome. Very different conditions exist near the break, where a H_2/steam jet enters the compartment atmosphere:

- the released gas is initially inert (no air)
- the combustible regime is entered from the rich side by mixing air/steam to the hydrogen/steam jet,
- high velocities and mass flows exist,
- high turbulence is created by shear flow and jet momentum dissipation.

Since deliberate ignition aims at early ignition as close as possible to the source to prevent hydrogen accumulation, it is important to evaluate the igniter concept for the characteristic conditions and flow regimes which exist near the H_2 release point.

2. OBJECTIVES

Large scale tests with dynamic hydrogen injection were performed with the following objectives:

- evaluation of ignitor efficiency under dynamic initial conditions in a confined and obstructed 3-d geometry,
- systematic investigation of the effects of ignitor position, ignitor frequency, hydrogen injection rate, and venting area on combustion loads,
- evaluation of the self-induced combustion modes after ignition, and
- use of results for optimization of deliberate ignition systems.

For technical, time and cost reasons the tests were performed without steam. Steam mainly acts as an inert dilutent which reduces the chemical reactivity of the system. This is analog to adding more air (nitrogen) or reducing the hydrogen concentration. No new principal phenomena are expected with steam.

3. EXPERIMENTS

3.1 *Test facility*

The experiments were conducted in the Russian RUT-facility near Moscow, which is a strong reinforced concrete structure with sufficient strength to withstand fully developed H_2-air detonations at ambient conditions. The test matrix was therefore not restricted by safety considerations, and the full spectrum of combustion modes could be explored.

Figure 1 shows the experimental volume which consists of a curved channel connected to a large room. The total volume is 310 m^3. Two concrete obstacles were placed in the channel (blockage ratio 30 %), and four steel wall-type obstacles into the large room. The test volume could be closed with steel plates at both ends of the channel.

The gas injection system consisted of a large H_2-reservoir at high pressure, an electric manometer for recording the reservoir pressure during injection, connecting pipes to the RUT facility, a remotely controlled main valve and an injection tube of 90 mm diameter. The hydrogen injection rate was controlled by the reservoir pressure and the chocked flow condition at the main valve.

Two different injection locations were used, designated by S1 and S2 in Fig. 1. In the first case the hydrogen jet was directed downwards at an angle of 45 degrees towards the nearest obstacles. In the second case injection was vertically upwards.

The ignitor positions for the source S1 were either I1 or I2, and for the source S2 either I3 or I4. The goal was to cover a large spectrum of injection directions (up and downwards), source-ignitor distances, and relative orientations between jet axis and source-ignitor connection line.

The diagnostics included three systems: 14 fast pressure transducers, 24 photodetectors for registration of flame positions, and 8 on-line hydrogen concentration gauges.The instrumentation allowed to measure the time and space dependent hydrogen distribution, evolution of the flame position, and combustion generated pressure loads.

3.2 *Test parameters*

The described set-up allowed to study combustion processes under conditions of dynamic H_2-injection into a confined and obstructed geometry of reactor relevant dimensions (310 m^3). The main experiment variables were:

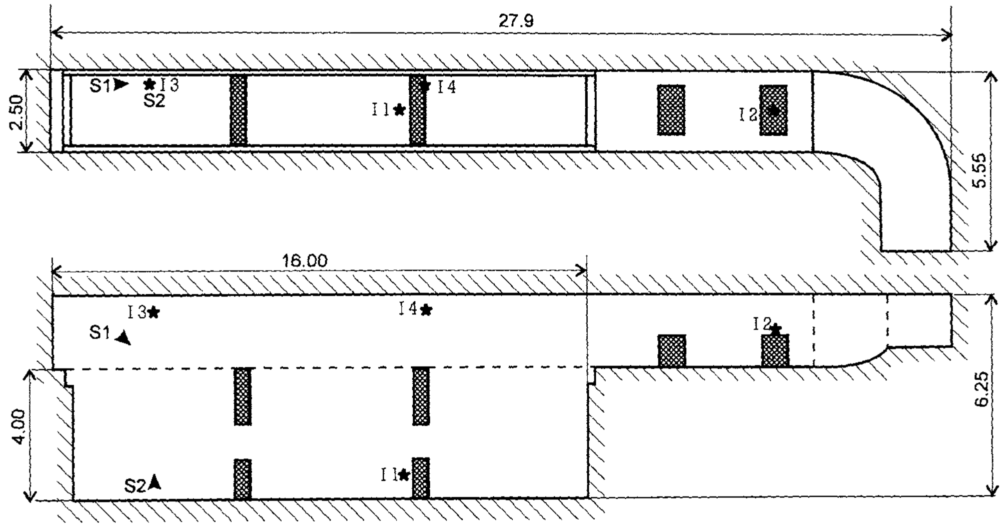

Fig. 1: Top and side view of the RUT test facility with H_2-injection locations (S1, S2), ignitor positions (I1 to I4), and obstacle geometry (shaded regions).

- hydrogen injection rate	0.1 - 1.2 kg H_2/s
- ignitor distance from source	5.25 - 20.8 m
- ignitor frequency	0.1 - 1 Hz
- vent area	0.3 - 4 m^2.

The chosen hydrogen injection rates cover the range typically predicted for severe accidents during the in-vessel core degradation phase of low pressure sequences involving a 1300 MWe core (DRS-B study). Since the injection direction is unpredictable the two main possibilities - upwards and downwards - were tested.

The selected ignitor distances from the source bracket most of the anticipated source-ignitor distances in the lower structures of a reactor containment.

Currently discussed ignitor frequencies are in the range of 1/10 to 1 Hz. The higher rate offers the possibility of earlier ignition, however on the expense of increased battery capacity. The tests were intended to provide some technical basis for the selection of an optimum spark frequency.

The vent areas used in the experiments vary from practically fully confined conditions (only 0.3 m^2 leakage area) to values which are typical for reactor containment compartments (of the order of 10^{-2} m^2 vent area/ m^3 volume $\approx$ 4 m^2/310 m^3). Exept for the 0.3 m^3 leakage are, the vent area was generally located far away from the main region of combustion, which impedes effective venting. This situation resembles the conservative, but possible situation, that the main combustion in a given room develops far away from the only door of that room.

Table 1 summarizes the test parameters of the 16 performed injection experiments. The main test objectives were: ignitor location and first spark time (hyd 24-29, 36-40), effect of venting (hyd 30-40), low injection rate (hyd 32-40), high spark frequency (hyd 34, 35), reproducibility (hyd 27, 29 and 32, 34), and rich mixtures (hyd 24, 28, 30, 31).

Table 1 Test parameters of dynamic hydrogen injection and ignition tests.

Test #	Hydrogen injection rate (kg/s)	Total injection time (s)	Time of first spark (s)	Time between sparks (s)	Ignition time (s)	Hydrogen source position (Fig. 1)	Ignitor position (Fig. 1)	Source - Ignitor distance (m)	Vent Area (m^2)
hyd 24	1.26	10.74	8.52	10	8.52	S1	I1	9.75	0.3
25	0.84	7.26	4.32	"	4.32	"	"	"	"
26	0.71	12.15	8.62	"	8.62	"	I2	20.80	"
27	0.60	7.35	13.97	"	33.97	"	"	"	"
28	0.99	11.60	69.10	-	69.10	"	"	"	"
29	0.59	7.98	14.3	10	34.3	"	"	"	"
30	0.68	8.1+8.1	14.04	"	260.8	"	"	"	4.0
31	0.73	25.46	1.4	"	21.4	"	"	"	"
32	0.10	58.5	2.75	"	52.75	"	"	"	"
33	0.12	55.0	60	"	no ignition	"	"	"	"
34	0.12	49.1	1.34	1	45.34	"	"	"	"
35	0.12	43.3	2.9	1	43.9	S1	I1	9.75	"
36	0.186	7.4	3.7	-	3.7	S2	I3	5.25	"
38	0.16	11.02	3.6	-	7.7	"	I4	9.75	"
39	0.148	11.32	23.9	-	23.9	"	"	"	"
40	0.184	7.1	18.4	-	18.4	S2	I3	5.25	"

4. EXPERIMENTAL RESULTS

The experiment progression can be separated into three phases, namely hydrogen distribution, hydrogen combustion, and load generation. The corresponding results and governing physical processes will be described in the following sections.

4.1 *Hydrogen distribution*

The hydrogen jet entered the initially stagnant air with velocities of around 700 m/s for injection rates of about 1 kg H_2/s. The high differential speed between both gases leads to turbulent entrainment of air in the H_2-jet. With increasing distance from the source, the average H_2-concentration and the velocity of the jet decrease due to mass and momentum conservation in the jet. Approximate models for the turbulent entrainment in free jets predict characteristic distances for the initial H_2-concentration and velocity decrease (factor e) which are of the order of 1 m. In the complex RUT-geometry the jet lost momentum also by interaction with obstacles and walls.

After turbulent dissipation of the jet momentum a relatively well mixed H_2-air cloud exists in some parts of the RUT facility, depending on location and direction of the H_2-jet source. The further motion of this cloud is governed by buoyancy forces and pressure differences. Since these two transport mechanisms produce little turbulence, the H_2-concentration of the air cloud is basically determined during the jet flow dissipation phase. The experiments indicate that the H_2-air cloud rises and spreads under the ceiling with increasing time. The cloud moves preferentially towards the vent opening, driven by the pressure difference to the environment.

Figure 2 shows as an example measured H_2-concentrations for test hyd 29. The data demonstrate that a hydrogen-air cloud developed in the left part of the facility, which rose to the ceiling, and then moved towards the right end of the channel. The cloud velocity decreased from initially 1.5 m/s to about 0.25 m/s. The rather well defined cloud boundary produced fast

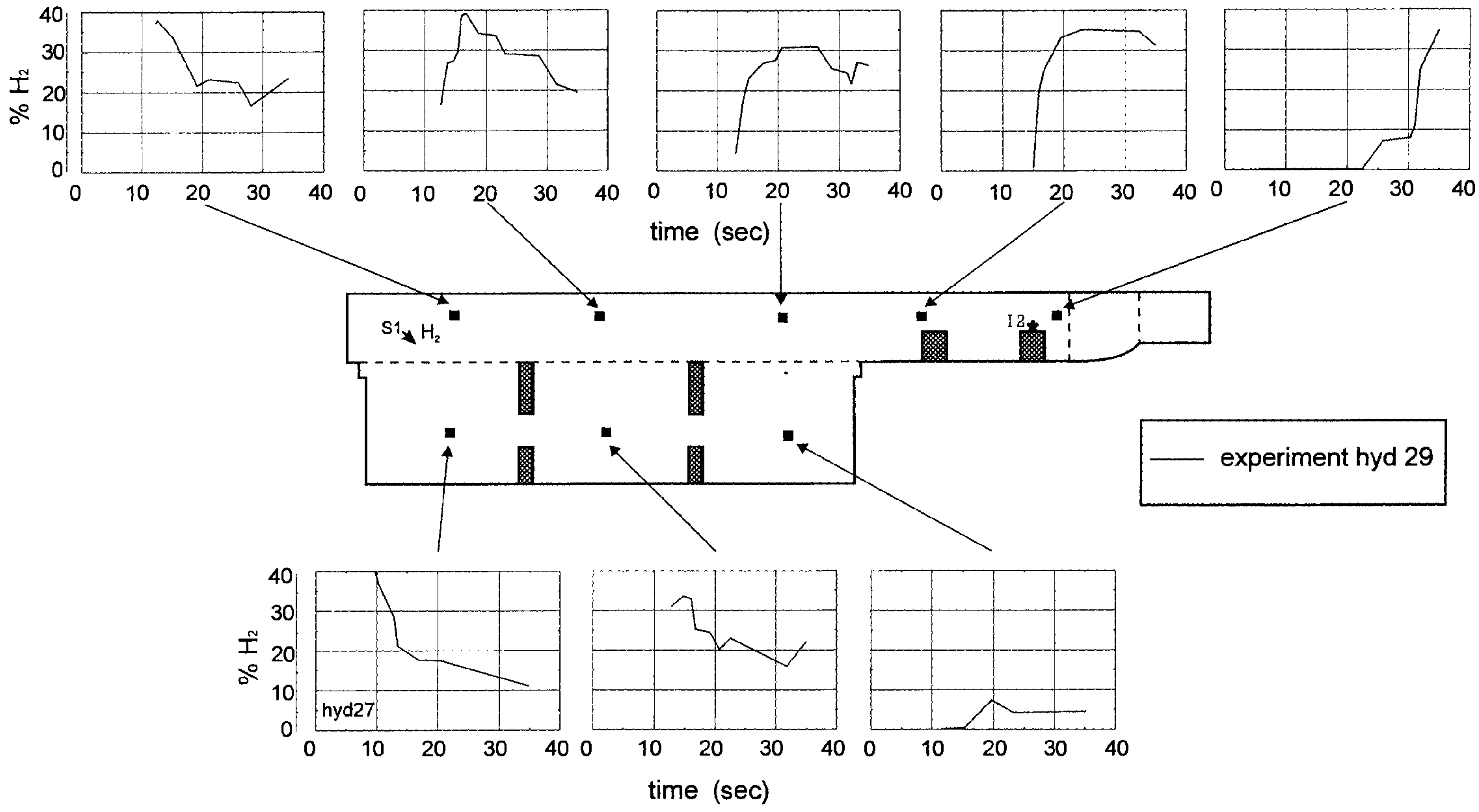

Fig. 2 Measured evolution of the local H_2-concentrations in experiment hyd 29. The H_2 jet created a well mixed H_2-air cloud by turbulent entrainment of air. The cloud then rose to the ceiling of the test section and moved to the right.

changes in the local H_2 concentrations (approx. 15 % H_2/s) as it moved to the right.

Ignition occurred in this test only after arrival of the cloud edge at the ignitor location (third spark at 34.3 s).

4.2 *Combustion processes*

Figure 3 summarizes the observed spectrum of combustion modes, which ranges from slow deflagrations to stable, fully developed detonations.

Slow deflagrations were observed for low hydrogen inventories at the time of ignition. The average H_2 concentration at ignition time, $\bar{x}_{H2}$, is calculated on the assumption that the injected hydrogen volume displaced the same volume of pure air through the vent openings. $\bar{x}_{H2}$ is a measure for the chemical reactivity of the system. The low H_2 inventories of test hyd 36 and 38 were due to the very short transport time of hydrogen to the ignitor. The ignitors were close to and above the source, so that both jet momentum and buoyancy carried the combustible H_2-air mixture to the ignitor location rapidly. A slow deflagration with maximum flame speeds of around 50 m/s developed in the shaded region of Figure 3. The flame may have attached to the source.

The combustion rate after ignition increases with increasing average H_2 concentration in the facility. Test hyd 25 started with a slow deflagration at the ignitor and reached a maximum flame speed of about 150 m/s in both directions within the instrumented test section. For a larger geometry a higher terminal flame speed would have been quite likely.

Experiment hyd 32 proceeded at an even higher average H_2-concentration and on a larger scale. The distance between the point of ignition and the source was 20.8 m. The initially slow flame accelerated after passing the first obstacle in the channel and entering the large test volume. The propagation velocity in the upper part of the facility was initially twice as fast as in lower parts, due to hydrogen stratification. A transition to detonation occurred in the lower left corner of the volume. Possible contributing factors are focussing of the precursor pressure wave in the corner and increased turbulence levels behind the left - most obstacle. The transition distance in this vented test was about 20 m.

The combustion in test hyd 24 proceeded in a very rich mixture due to the large H_2-injection rate used (1.26 kg/s). Fully developed detonations were established only 4 to 6 m away from the ignitor in both directions. Both DDT locations are situated behind the nearest obstacles, indicating very fast flame acceleration and transition in this rich mixture. The two detonation fronts propagated throughout the remainder of the test volume.

One of the most severe combustion events developed in test hyd 26, although the total H_2 inventory was similar to other less violent experiments (e.g. hyd 32). An early transition to detonation occurred at the entrance to the large volume, probably driven by high local turbulence in the unburned gas at the flow cross section enlargement. The fast flame acceleration was supported by the low venting in this test (0.3 m^2 leakage area). The detonation proceeded along the ceiling with speeds of about 2100 ($\pm$ 100) m/s. This corresponds to theoretical CJ-detonation velocities of H_2-air mixtures between 30 and 50 % H_2.

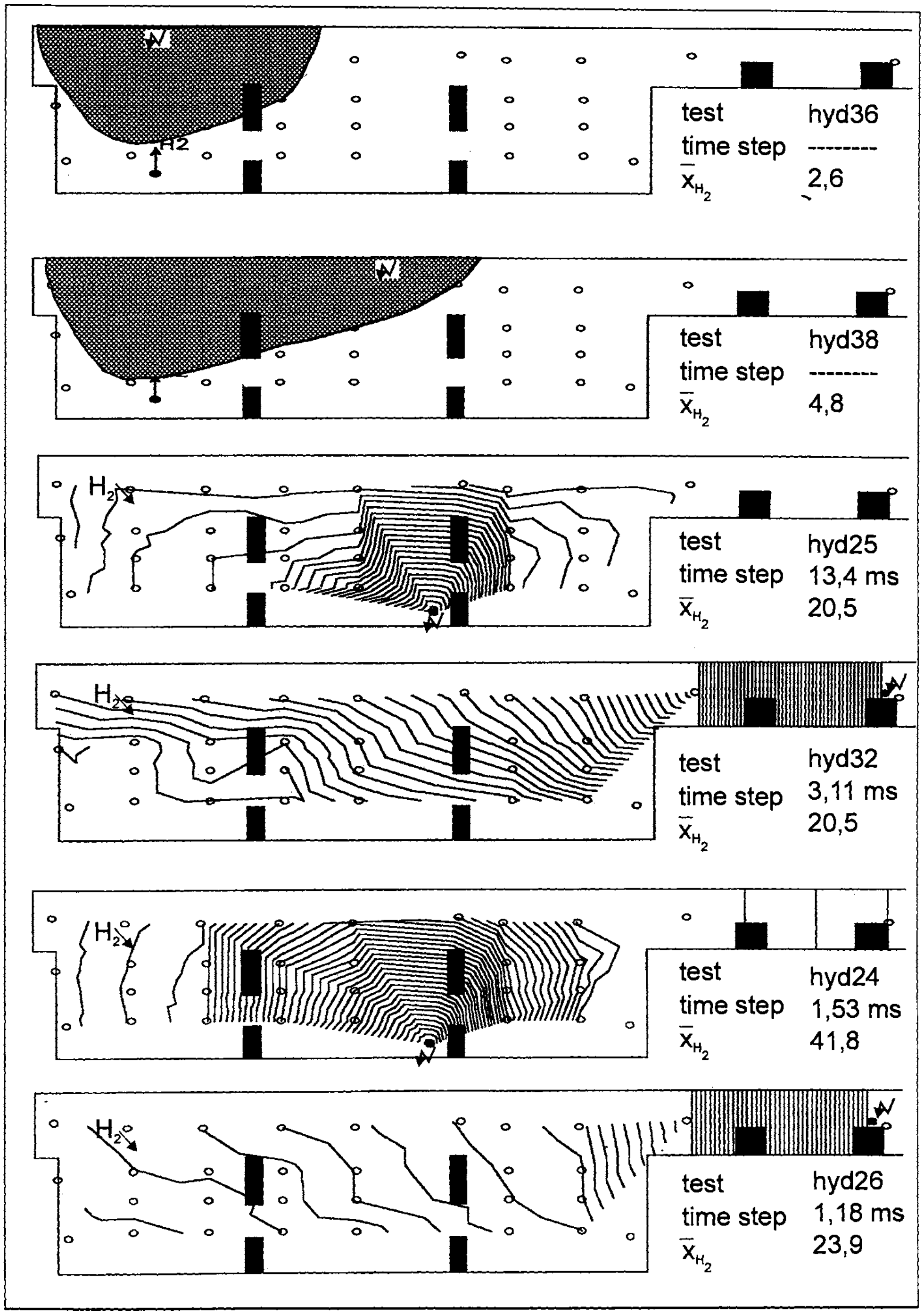

Fig. 3 Observed combustion regimes with dynamic H_2-injection into air. The combustion spectrum ranged from slow deflagrations (top) to fully developed stable detonations (bottom). Controlling factors are the H_2-inventory at the time of ignition ($\bar{x}_{H2}$) and the distance between source and ignitor.

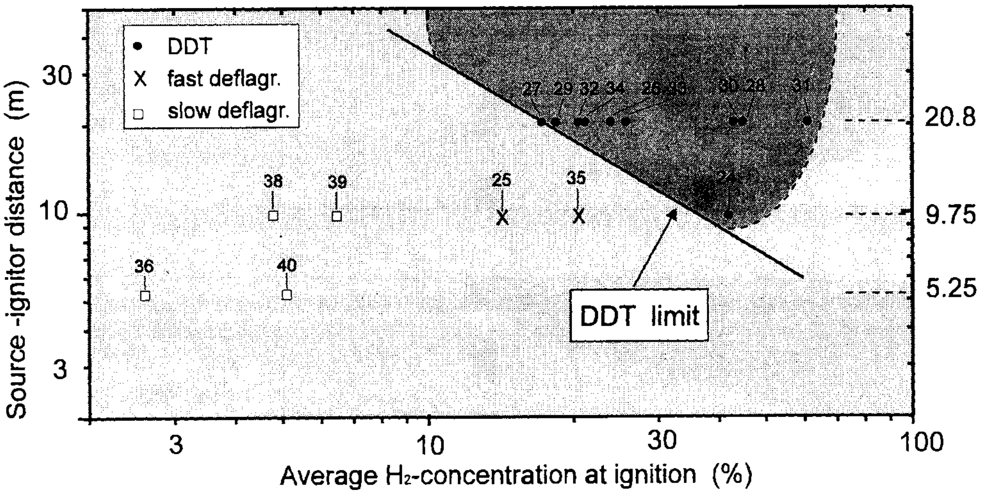

Fig. 4 Summary of combustion regimes observed in dynamic H_2-injection tests hyd 24 to 40. An inverse relation between source-ignitor distance and average H_2 concentration separates the deflagration from the detonation regime (DDT limit).

The observed combustion modes are summarized in Figure 4 by using as variables the average H_2-concentration in the facility at the time of ignition and the distance between source and ignitor. These variables characterize the chemical reactivity and the geometrical scale of the H_2-air cloud. Detonations were observed in the dark colored region. A limit for this region is given by $d = C/\bar{x}_{H2}$. This is in accordance with earlier observations which have shown that increasingly less reactive mixtures can undergo a DDT with increasing scale (Dorofeev, 1995). The known combustion properties of the H_2-air system suggest that the boundary on the rich side should increase again with increasing H_2-concentration according to the dotted curve.

The main controlling factors for the observed combustion modes are the H_2-concentration of the cloud, the scale of the reacting H_2-air cloud, the flow induced turbulence from obstacles and changes in the flow cross section, and the degree of confinement.

4.3 *Pressure loads*

The generated pressure loads are strongly related to the flame speeds which developed during the combustion process. One example is discussed below for a slow deflagration, a fast turbulent deflagration, and a stable detonation.

A slow deflagration occured in test hyd 39, due to the low H2-inventory. A the time of of ignition the 4 upper left H_2-sensors (Figure 2) showed H_2 concentrations between 7 and 22% the lower 3 H_2 sensors showed values between 1 and 3%. A strong stratification developed during and after

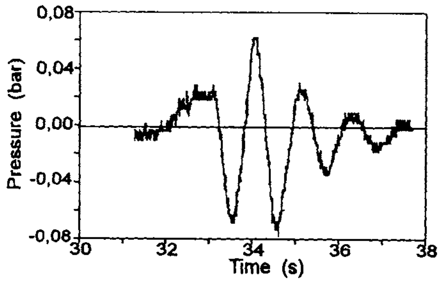

Fig. 5: Pressure load from a slow deflagration experiment (hyd 39). The load is of long duration and low amplitude

H_2 injection. The combustion of the cloud resulted in pressure waves of long duration (≈ 1 second) and low amplitudes (< 0.08 bar), (Fig. 5). The flame velocity was less than 10 m/s.

An accelerating flame was observed in test hyd 32 (see Fig. 3) which lead to a local detonation after about 20 m travel distance. The pressures measured in the lower part of the facility are shown in Fig. 6. The given x dimension is the horizontal distance of the transducer from the left wall of the test facility (Fig. 1).

Initially (after 0.22 s) the pressure rose slowly and simultaneously at all transducer locations, indicating a sub-sonic flame. At about 0.249 s a strong detonation peak is recorded at the location 0.89 m. Reflection and focussing of this detonation wave in the lower left corner produced a local peak overpressure of 40.7 bar at the left wall of the facility. The reflected shock propagated back towards the ignitor and caused the highest peak pressures at all other locations during the experiment. The succeeding shock reverberations caused multiple load peaks at later times.

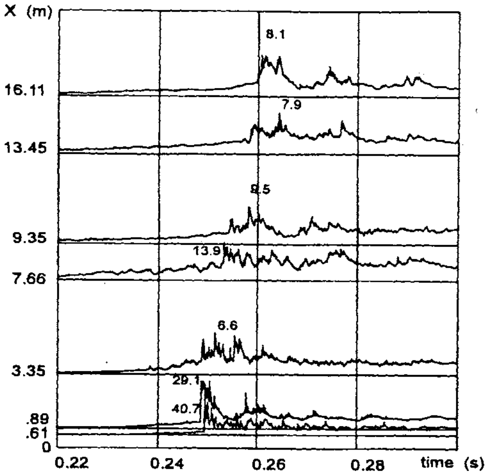

Fig. 6: Pressure load from an accelerating flame leading to a local detonation in the facility. The reflecte detonation shock caused multiple load peaks at all other locations.

A stable detonation was observed in test hyd 26. Fig. 7 shows measured pressure histories in the upper part of the volume. Ignition was at location x = 22.8 m. First a slow pressure rise developed from a slow burn in the channel. After passing the first obstacle, pressure oscillations are visible from an accelerated turbulent flame (x = 17.64 m). A full detonation was established at 11.44 m. The DDT occurred within few meters of the entrance to the large volume. The stable detonation propagated throughout the remaining H_2-air cloud up to the to the end of the facilitywith about 1990 m/s. The detonation peak pressures and thelong term pressures are similar to those measured in earlier premixed detonation tests, having approximately the same hydrogen concentration (20-25% H2), (Breitung, 1994). These results suggest that DDT loads under dynamic initial conditions are similar to detonation loads from H_2-mass equivalent premixed conditions.

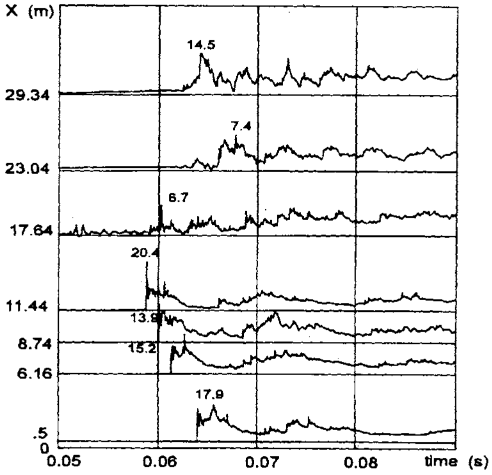

Fig. 7: Pressure load from a stable detonation in the large section of the test volume. The loads are similar to those from premixed conditions with the same H_2 inventory.

5. DATA ANALYSIS

5.1 *A model for DDT limits*

The experiments have shown that the combustion process and the resulting pressure loads are governed by the total amount of hydrogen released up to the time of ignition. This mass is determined by the H_2 release rate $\dot{m}$, the transport time from the source to the ignitor t_{tr}, and the spark intervall Δt. The maximum amount of hydrogen which can be released up to the time of ignition is

$$m_{H2} = \dot{m}\,(t_{tr} + \Delta t) \qquad (1)$$

Release of this H_2-mass into an air filled volume V at pressure p and temperature T produces an average H_2-concentration of

$$\bar{x}_{H2} = m_{H2}\,RT/M_{H2}\,pV \qquad (2)$$

where $M_{H2} = 0.002$ kg/mol H_2, and assuming air displacement by the injected hydrogen. The transport time of the H_2-air cloud can be expressed by the average transport velocity v and the source-ignitor distance d ($t_{tr} = d/v$), resulting in

$$\bar{x}_{H2} = \frac{RTm}{M_{H2}\,pV}\left(\frac{d}{v} + \Delta t\right) \qquad (3)$$

The average transport velocity v contains contributions from the initial jet flow, from the buoyant rise of the H_2-air plume, and from displacement flows towards vent openings. The velocity v will be determined by the details of the flow field developing in the compartment. Average transport velocities for the RUT-tests were estimated from the known ignitor distance and the measured time of ignition. For distant ignitors which are outside of the direct jet flow, the typical average transport speed of the H_2-cloud is 0.5 - 1 m/s. For ignitors located in the jet flow region, velocities above 2 m/s were observed in the RUT tests.

The experiments indicated a certain region in which DDT events were observed (Fig. 4). A boundary for this region is given by

$$d = C/\bar{x}_{H2}, \quad \text{with } C = 3.5\text{ m} \qquad (4)$$

Replacing $\bar{x}_{H2}$ in Eq. (3) results in the following relation between the variables of interest:

$$d^2 + v\,\Delta t\,d - v\,C M_{H2}\,p\,V/RT\dot{m} = 0 \qquad (5)$$

Eq. (5) predicts limiting values for the variables of interest like d, $\dot{m}$, v, or Δt, below which no DDT should occur.

5.2 *Model applications*

For the case of small spark intervals ($\Delta t \ll d/v$) the maximum allowable source-ignitor distance for DDT prevention becomes

$$d_{max} = (v\,C\,M_{H2}\,p\,V/RT\dot{m})^{1/2} \qquad (6)$$

For typical RUT test conditions the result is d_{max} = 9.4 m. (v = 0.5 m/s, C = 3.5 m, M = 0.002 kg/mol, p = 10^5 Pa, V = 300 m^3, R = 8.314 J/molK, T = 283 K, $\dot{m}$ = 0.5 kg/s).

Eq. (6) also predicts critical release rates for the case of high ignitor spark frequency. For the given example an ignitor at 9.4 m distance could safely handle a flow of up to 0.5 kg H_2/s. For higher release rates a local detonation could not be excluded, based on the current experiments.

Another point of interest for the ignitor concept concerns the spark interval Δt. The main requirement from Eq. (3) is that the spark interval should be significantly shorter than the transport time d/v, in order to minimize the hydrogen inventory at the time of ignition. For the typical transport times observed the RUT tests (10 to 20 s), this relates to maximum spark intervals of few seconds.

Another way of minimizing the total H_2 release before ignition is to maximize the transport velocity v. This can be achieved by placing the ignitor in the path of potential flow directions, e.g. in or near expected jet flows, at high elevations in the room (buoyant rise), or between source and vent openings (vent flows).

The presented model allows to predict tendencies and principal effects of ignitor variables on the capability to prevent DDT and local detonations. For containment applications more work with multidimensional flow simulation codes like GASFLOW is needed to make reliable quantitative predictions of the dominant flow directions and average transport velocities for different locations, directions and mass flow rates of the H_2/steam jet.

The presented model provides conservative DDT limits from the view point of gas composition, because the tested H_2-air mixtures had the highest possible chemical reactivity of all mixtures relevant for severe accidents (no steam, no nitrogen enrichment). On the other the low RUT temperaturs (10 °C) decreased the chemical sensitivity compared to typical severe accident tempeatures (100 ± 50 °C). The influence of the RUT vent configuration on the measured DDT results (Fig. 4) will probably depend on the H_2-concentration. Large scale experiments with premixed 24.8 % H_2 in air indicated that small degrees of transverse venting promote DDT due to local turbulence at the vent openings. (Sherman et al). This DDT mechanism is not active in the longitudinal venting of the RUT tests. On the other hand in case of lower H_2 concentrations with lower flame speeds and more time for venting of burned and unburned gases, additional transverse vent openings (compares to RUT) should diminsh flame acceleration and impede this mode of DDT.

6. CONCLUSIONS

Experiments with dynamic H_2 injection into air have been performed to investigate the consequences of deliberate ignition near the hydrogen release point.

The measurements have shown that a wide spectrum of combustion processes can occur under dynamic initial conditions, depending on test variables. The combustion mode and the resulting pressure loads are determined by the following physical processes.

Hydrogen distribution is governed by three driving forces: jet momentum, buyoancy forces, and pressure differences. The mixing of hydrogen and air occurs mainly during the jet flow dissipation by turbulent entrainment of air. The rather well mixed H_2-air cloud later moves with relatively small changes in composition, through the available volume.

Ignition occurs only after the edge of the cloud, has arrived at the ignitor location and the next spark has been triggered. The flame travels back from the ignitor towards the source. The resulting flame speed and combustion mode depend mainly on the H_2-inventory in the system at the time of ignition, which can be expressed by the average H_2-concentration at the time of ingition ($\bar{x}_{H2}$). The second governing factor is the scale of the reacting cloud (d). A relation between $\bar{x}_{H2}$ and d was derived from the experimental data, which separates the deflagration from the detonation regime (Fig. 4).

The pressure loads are strongly related to the flame speeds. In cases of slow deflagration pressure waves of long duration and low amplitudes are generated. The opposite extreme in combustion speed is represented by fully developed stable detonations. The loads from these detonations, which originated from dynamic initial conditions, are similar to those from homogeneous mixtures with the same H_2-inventory.

The experimentally determined DDT-limit (Fig. 4) was used to derive a limiting relation between source properties (location, H_2-release rate), compartment properties (volume, temperature, pressure) and ignitor properties (location, spark frequency). This relation can be used to estimate quantities like the maximum safe distance between source and ignitor, the maximum safe H_2 release rate, or the minimum spark interval, needed to prevent a DDT in the compartment. Using these new results, spark ignitor systems can be taylored specifically for each compartment to achieve maximum effectiveness in preventing a DDT event.

REFERENCES

Breitung, W., Dorofeev, S.B.; Efimenko, A.A., Kochurko, A.S.; Redlinger, R., Sidorov, V.P. 1994. Large scale experiments on hydrogen-air detonation loads and their numerical simulation. Proc. Int. Top. Meeting on Advanced Reactor Safety (ARS-94), Vol. 2, p. 733, April 17 - 21, 1994, Pittsburgh, PA, U.S.A.

Dorofeev, S.B., Sidorov, V.P., Droinishnikov, A.E, Breitung, W., 1995. Deflagration to detonation transition in large confined volumes of lean H_2-air mixtures. Submitted to Combsution and Flame.

DRS-B study, 1990. Deutsche Risikostudie Kernkraftwerke - Phase B. Gesellschaft für Reaktorsicherheit, Verlag TÜV Rheinladn, Köln, Germany.

Heck, R, 1992, Concept and qualification of a combined system for hydrogen mitigation after severe accidents. *Hydrogen behaviour and mitigation in water-cooled nuclear power reactors.* E. Della Loggio (Ed.), Commission of the European Communities, EUR 14039 EN.

Kanzleiter, T., 1992. Hydrogen deflagration experiments in a multi-compartment containment geometry, Hx-tests. Final report Battelle Frankfurt, BIeV-R66.985-01.

Projekt HDR-Sicherheitsprogramm (PHDR), 1994. Untersuchungen zur Wasserstoff-Deflagration in einem Reaktorcontainment. Report PHDR 126 - 94, Forschungszentrum Karlsruhe, Germany.

Sherman, M.P, Tieszen, S.R. Bededick, W.B., 1989, FLAME facility. Report NUREG/CR-5275, SAND 85-1264, Sandia Natl. Laboratories, Albuquerque, 87185 NM, U.S.A.

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