APPENDIX E: DDT EXPERIMENTS IN SHOCK TUBE AND OBSTACLE ARRAY GEOMETRYy *

E.1 Recent DDT Experiments at FZK

Appendix E presents selected results of recent experiments conducted at FZK [E.1] on three different modes of DDT that are relevant for nuclear safety investigation and risk analysis:

- focusing of pressure and shock waves produced by bursting vessels or pipes,

- focusing of precursor pressure and shock waves generated by an accelerating flame,

- DDT within or near the turbulent flame brush of a flame accelerating in an obstructed and highly confined part of the containment.

E.1.1 Experiment Design

Three test series addressing these different DDT modes were performed in the FZK combustion tube (12 m long, 35 cm ID). The corresponding test configurations are displayed in Figure E.1.1-1:

a. Shock tube with conus

The tube was divided by a membrane into a low-pressure section (LPS, length 9 m) and a high-pressure section (HPS, length 1 or 3 m). The experiments were conducted with a conical reflector at the end of the low-pressure section to focus the pressure wave and to reach self-ignition temperatures (Figure E.1.1-2). The main idea behind this experiment design is the observation that in many tests with fast combustion modes, DDT events are apparently triggered by waves reflected in corners or other converging multi-dimensional parts of the enclosure. The conus is used to produce local hot spots in the combustible gas because hot spots generally develop from the interaction of a pressure wave with a complex multi-dimensional target.

After evacuating both sections, the low-pressure section was filled up to the desired initial pressure with a defined hydrogen-air mixture. The parameters that changed during the experiments were the initial pressure (0.5 to 1.5 bar) and the composition of the hydrogen-air mixture (9% to 30% H_2). The high-pressure section was filled with helium up to membrane failure. To detect DDT processes, pressure transducers, photodiodes, and film thermocouples were located along the tube. Ionization gauges were installed in and near the conus.

b. Partially obstructed shock tube with conus

About half of the tube was equipped with an array of ring obstacles blocking 30% of the flow cross-section (BR = 30%) over a length of 5 to 6 m to accelerate the flame to a high velocity. The tube also contained a conus to focus the precursor shock wave.

The main idea behind this experimental set-up is that after a weak spark ignition, the propagation flame reaches a highly obstructed region in which it can accelerate because of the generation of intense turbulence. This fast flame then emits precursor pressure waves that can propagate through a relatively open region until they are reflected from the enclosure. In most practical cases, the precursor wave will not simply be normally reflected from a flat wall but rather will be focused by two walls

* Dr. W. Breitung is the lead author of Appendix E.

(2D wedge) or three walls (3D corner). Such focusing geometries in industrial buildings were simulated in the tube tests by a conical reflector situated at the end of the tube, opposite to the ignition location. The investigated tube geometry contains therefore all characteristic elements of a combustion sequence in a complex nuclear containment. These are

- a combustible gas,
- a weak ignition source,
- a partly blocked region with flow obstacles producing high turbulence levels,
- an open region that permits pressure wave propagation without significant losses, and
- a multi-dimensional reflector as part of the enclosure.

The tube was evacuated and then filled with a defined hydrogen-air mixture (9% to 30% H_2) to the initial pressure (1 bar). The mixture was ignited with a glow plug. Pressure transducers, ionization gauges, photodiodes, and film thermocouples were used to locate possible DDT events.

c. Fully obstructed tube

The combustion tube was equipped with an array of ring obstacles (BR = 60%) over its full length of 12 m. The evacuated tube was filled with a defined hydrogen/air mixture (9% to 20% H_2) up to the initial pressure (0.5 to 2.0 bar) and was then ignited with a glow plug. To observe the combustion processes, pressure transducers, photodiodes, and film thermocouples were located along the tube.

E.1.2 Results of DDT in a Shock Tube with Conus

Three criteria can be used to determine whether a detonation initiation occurred. The first is the velocity of the reflected wave, the second is coupling or decoupling of pressure and light signals, and a third method is to analyze the pressure amplitudes and profiles along the tube. At given times, the pressures at each pressure transducer location can be collected and depicted as function of tube location. The spatial distribution of the pressure gives clear indications about the existence of a deflagration or detonation.

Figure E.1.2-1 shows the x-t diagrams obtained in two experiments with 15% H_2 in air, one leading to a mild ignition without detonation (top) and one leading to DDT (bottom). In the first case, the Mach number of the incident shock wave (ISW) was measured to M = 1.93, and the reflected shock wave (RSW) initially reached 506 m/s, which is close to the speed of a normally reflected inert wave without combustion. The measured trajectories for the flame and the RSW separate soon after the flame-shock complex leaves the conus, well before the expected arrival of the He-contact surface.

Increasing the Mach number only slightly to M = 2.01 results in very different findings. The measured RSW velocity obtains 1333 m/s, which is close to the theoretical CJ detonation speed in the countermoving H_2-air mixture. (wave speed W in laboratory frame is D_{CJ} minus particle velocity u behind the incident shock: $W = D_{CJ} - u$.). In addition, the RSW and the flame front remain coupled until they come close to the contact surface. These are clear indications of a detonative combustion returning from the conus.

The measured pressure profiles along the tube are compared in Figures E.1.2-2 and E.1.2-3 for two other experiments with 15% H_2 in air.

Figure E.1.2-2 is the case with mild ignition. Curves 1, 2, and 3 represent pressures of the ISW, and curves 4, 5, 6 those of the RSW. These reflected pressures are only slightly higher than those measured for the inert case without hydrogen in the LPS [E.1], except that the maximum pressure in the conus reaches almost 40 bars, compared with only 8 bars in the inert case. These values indicate that a local explosion kernel was created in the focus but that it decayed to a slow deflagration outside of the conus.

Figure E.1.2-3 shows the measured pressure profiles for the strong ignition case with DDT. The pressure profiles of the incoming shock are similar to the pressure profiles shown in Figure E.1.2-2, but the reflected pressure profiles closely resemble those of CJ detonations. Note that the initial pressure in the LPS was only 0.45 bar, which indicates that the detonation decayed from an overdriven state towards CJ conditions as it propagated away from the reflector. In addition, the higher RSW velocity and the observed coupling between light and pressure supports the conclusion that DDT occurred in this experiment.

Based on these three indicators -namely reflected wave speed, coupling between light and pressure and magnitude and shape of pressure distribution- the experiments could be grouped clearly into cases with and without DDT.

Figure E.1.2-4 shows a summary plot containing the test results with H_2-air mixtures between 10% and 30%H_2. The dashed lines indicate the critical Mach numbers for the respective mixtures at which the reflected wave velocity suddenly switches from typical inert values (lower line) to detonation-like values (upper line). A very low Mach number was found for stoichiometric H_2-air mixtures, demonstrating that DDT can be easily achieved if such mixtures should be present in a multi-dimensional enclosure and a pressure wave should be generated by a bursting pipe or vessel.

Corresponding experiments in a geometrically similar, but scaled-down laboratory shock tube showed the same general trend for the transition from mild to strong ignition, however at consistantly higher Mach numbers [E.2]. The linear scaling ratio between both facilities was 6.5.

Very good reproducibility of individual tests and consistency of the whole database in terms of ignition modes was observed. The detailed processes in the focusing tests are highly mechanistic and seem to be governed by the temperature-dependent reaction kinetics.

The shown data are useful for development of first numerical models because mainly flow dynamics and reaction kinetics are involved, and not complex turbulent combustion.

E.1.3 Results of DDT in a Partially Obstructed Tube with Conus

One example for a DDT driven by flame-generated precursor waves is presented in Figure E.1.3-1, which shows an enlarged part of the R-t diagram near the conus (9.75 to 12.00 m). The precursor wave from the accelerating flame travels into the conical reflector at 750 m/s, causing a strong self-ignition in the focus.

This ignition is detected simultanesouly by the photodiodes, the ionization gauges, and the pressure transducers. The measured pressures initially exceed the theoretical CJ pressures indicating an overdriven detonation. ($p_{CJ}/p_0 \approx 11.2$ for 16.5% H_2 in air.) The flame front and the RSW remain coupled and travel with a measured velocity of 1360 m/s. Such a velocity is typical for a detonation in the counterflowing gas, indicating that a DDT event has occurred.

All experiments performed in the partly obstructed geometry can be grouped into three regimes:

- At low hydrogen concentrations (≤ 11%) the speed of the propagating flame in the obstructed zone remains much slower than the speed of sound in the unburned gas. The flame emits a set of acoustic waves, and the pressure increases practically uniformly in the tube according to the fraction of gas burned at any given time.

- In the second regime, which occurs for hydrogen concentrations from about 12% to 18% (at $p_0 = 1$ bar, $T_0 = 300$ K) a coupled flame/shock complex is emitted from the obstacle section. Because of the flame deceleration in the smooth unobstructed part of the tube, a shock wave proceeds from the flame. The shock is faster than the flame. Depending on the Mach number, the precursor wave can trigger a weak (deflagrative) or a strong (detonative) ignition when it is reflected at the tube end.

- A third regime is observed when the hydrogen concentration exceeds 18%. In this case, the flame and shock complex remain coupled after the complex leaves the obstructed region, at least for the travel distance available in the present test set-up. Flame and shock have the same velocity. The interaction of this complex with the tube end causes only a reflected wave back into combustion products, and contrary to regime (2), no secondary ignition can occur.

DDT from fast flame precursor waves is only possible in the second regime where the shock velocity exceeds the flame speed. The corresponding measured range of hydrogen concentrations (12% to 18%) is not universal; it will generally depend on the tube dimensions and details of the obstacle section (length, blockage ratio). Experiments in a geometrically similar but scaled-down facility of the Russian Academy of Sciences (linear scale 1:6) have identified the same three regimes but at hydrogen concentrations that were several percent higher than in the FZK-tube tests [E.3].

The three described regimes lead to different load mechanisms and load magnitudes. In the first case ($v_{flame} \ll c$), the pressure increases nearly uniformly in the tube. The pressure increase at a given time is proportional to the fraction of burned gas at that time. Shape and size of the reflector have no influence on local pressure loads.

In the second regime ($v_{flame} < v_{shock}$), two effects lead to higher loads compared with the loads in the first regime:

1. directed flow with particle velocities of the order of several 100 m/s, and

2. secondary ignition after reflection in the multi-dimensional target at the tube end.

For low shock velocities, which only trigger a deflagration, the additional loading from the secondary ignition is not substantial. The pressure loads are comparable to those of an inert reflection. However, in case of sufficiently high shock speed, the strong secondary ignition causes very high local pressures because the chemical reaction proceeds from a pre-compressed state.

Compared with the loads in the second regime, the third regime ($v_{flame} = v_{shock}$) produces lower pressures and impulses. The particle velocities of the directed flow increase, but this is more than compensated by the fact that no secondary ignition can result from the reflection process.

In summary, the highest loads were observed inside the 3D reflector in the second regime under DDT conditions. In this case, the flow was directed into the conus pre-compressed unreacted gas, which then ignited rapidly. An overdriven detonation propagates away from the reflector into the rest of the unburned gas.

E.1.4 Results of DDT in a Fully Obstructed Tube

An example of DDT in or near a turbulent flame front is presented in Figure E.1.4-1 for a flame acceleration test with 16.5% H_2 in air. The top figure shows that coupling between the visible light front (flame brush), and the pressure front occurs between the 5.25 m and 6.25 m positions. The pressure amplitudes and shapes change from deflagration to detonation-like in the same region (bottom figure). The detonation-like pressure profile is stable for the rest of the combustion up to the tube end.

The flame velocity measured in this test is depicted in the lower left corner of Figure E.1.4-2 The DDT event seems to cause a locally overdriven detonation, which then relaxes to a stable quasi-detonation with near-CJ velocity (1577 m/s for this mixture).

The other data shown indicate consistently that the transition process requires a flame velocity of about 800 to 900 m/s, which is close to the isobaric speed of sound in the combustion products (sound speed in Figure E.1.4-2).

E.2 References

[E.1] A. Veser, W. Breitung, G. Engel, G. Stern and A. Kotchourko, Deflagration-to-Detonation-Transition Experiments in Shock Tube and Obstacle Array Geometries, Report FZKA-6355, Research Center Karlsruhe, P.O. Box 36 40, 76021 Karlsruhe, 1999.

[E.2] B.E. Gelfand, S.V. Khomik and S.B. Medvedev, Investigation of Hydrogen and Air Fast Flame Propagation and DDT in Tube with Multidimensional Endplates, Research Report No.2, Institute of Chemical Physics, Russian Academy, 1997.

[E.3] B.E. Gelfand, S.V. Khomik and A.N. Polenov, DDT Experiments with Focusing of H_2-Air Blast Waves, Final Report, Institute of Chemical Physics, Russian Academy of Sciences, Moscow, to Forschungszentrum Karlsruhe, 1998.

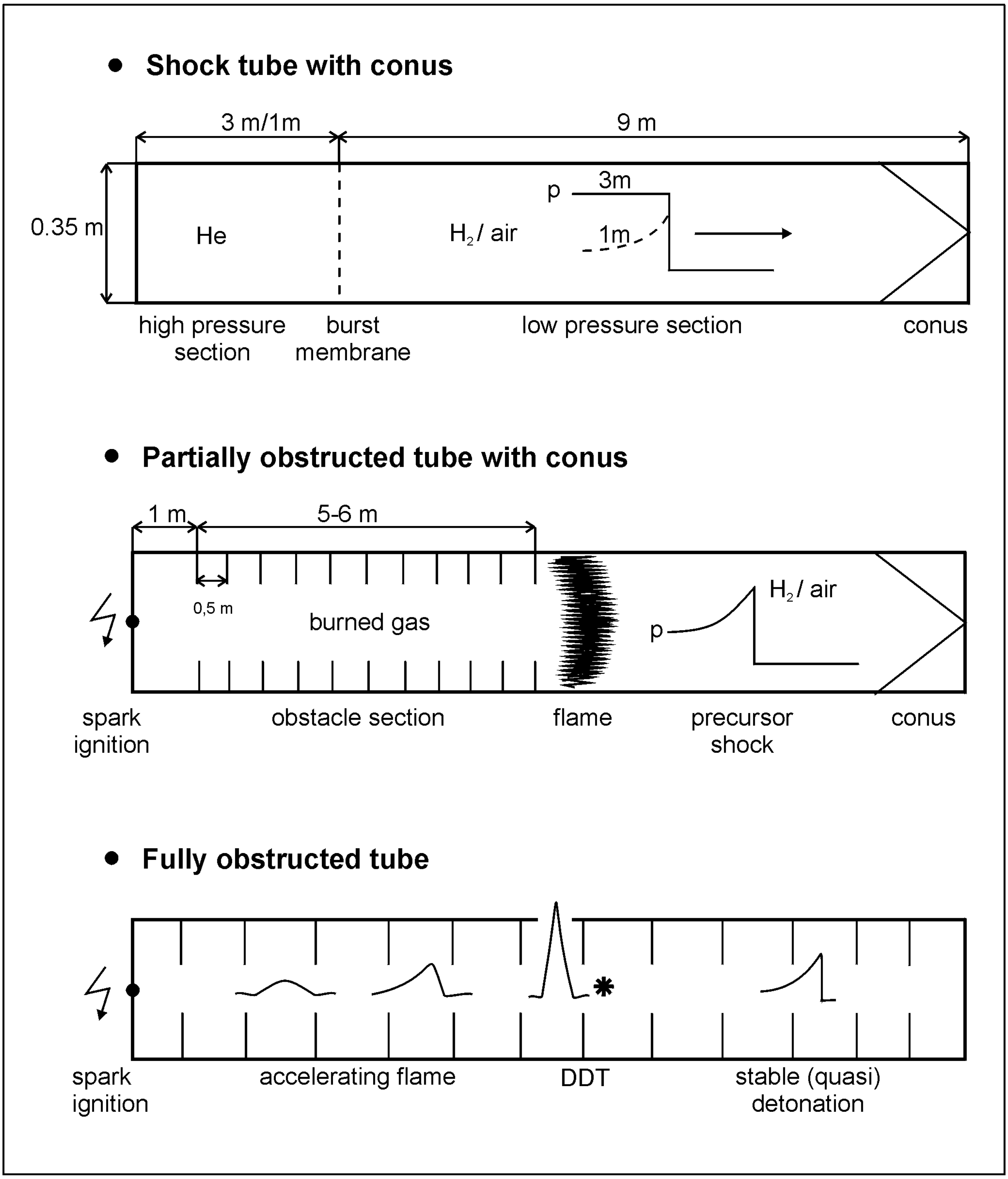

Figure E.1.1.-1 FZK experiments on three different DDT mechanisms using three experimental configurations of the 12 m tube. Pressure transducers, photodiodes, film thermocouples, and ionization gauges were used for instrumentation.

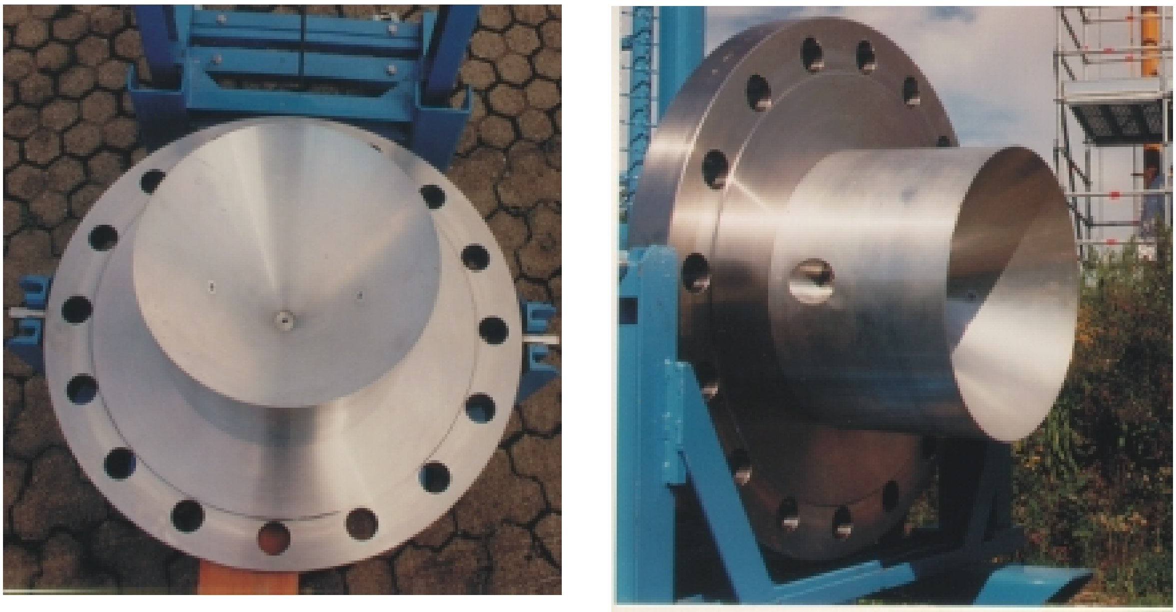

Figure E.1.1.-2 Photographs of the conus used to produce local hot spots for self-ignition of the test gas. The conus diameter, length, and opening angle are 35 cm, 21 cm and 70°, respectively. Three pressure transducers are installed inside the conus.

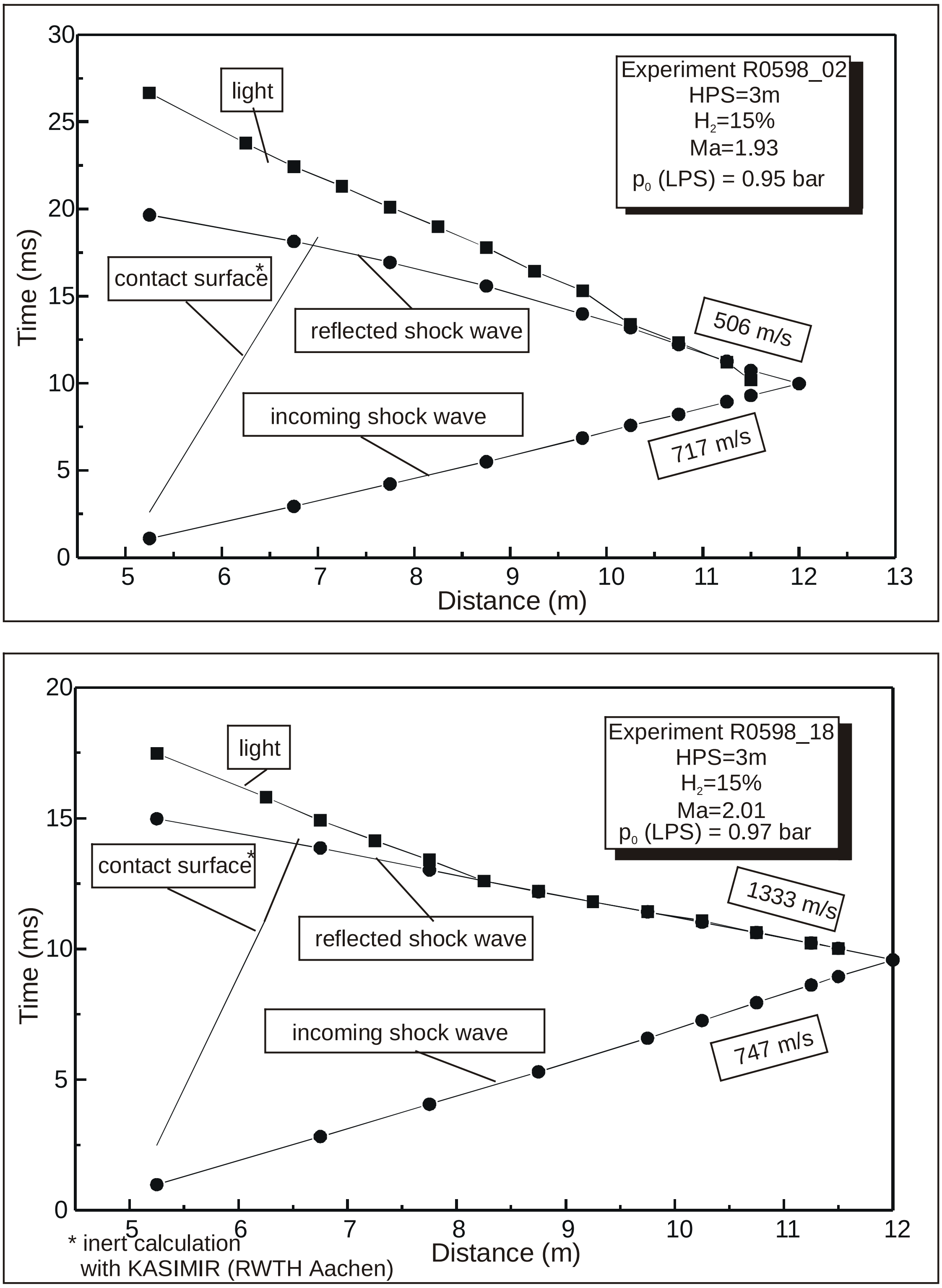

Figure E.1.2-1 Example of measured flame and shock trajectories for 15% hydrogen in air. Upper case leads to weak ignition (decoupling of pressure and flame front); lower case has strong ignition and leads to DDT (stable pressure/flame complex and detonation typical speed of reflected shock wave).

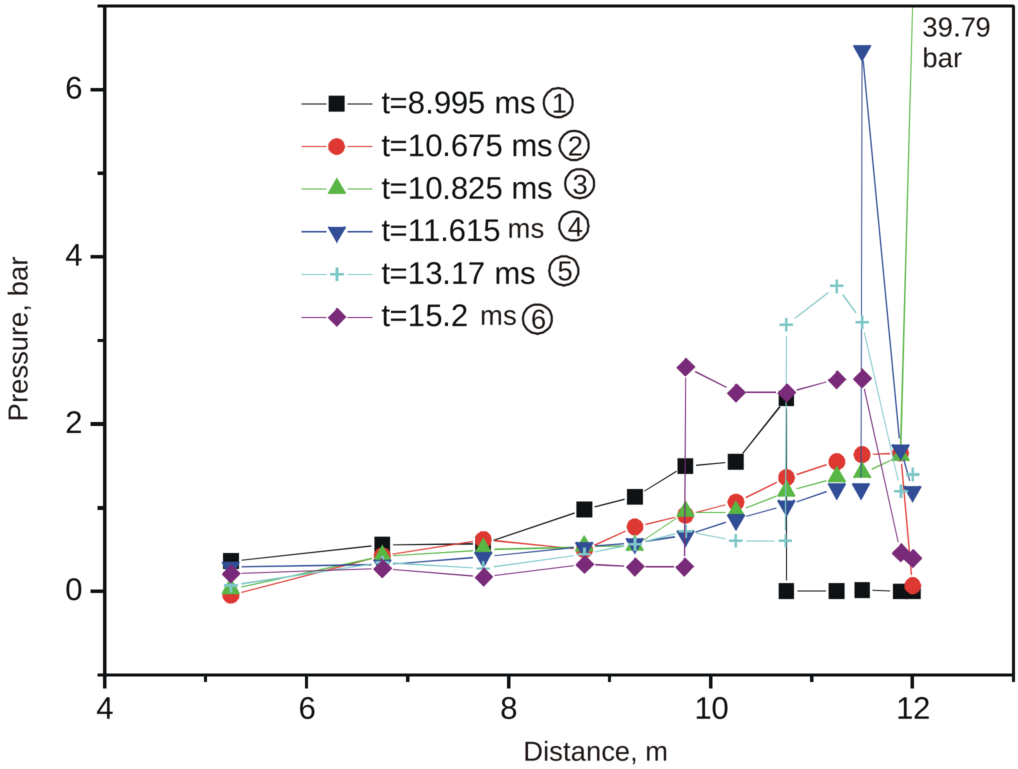

Figure E.1.2-2 Measured pressure profiles along the tube at given times. Initial conditions: 15% hydrogen in air, pressure in LPS 0.7 bar, pressure in HPS 6.7 bar, Ma = 1.77. Measured velocity of reflected shock wave 480 m/s.

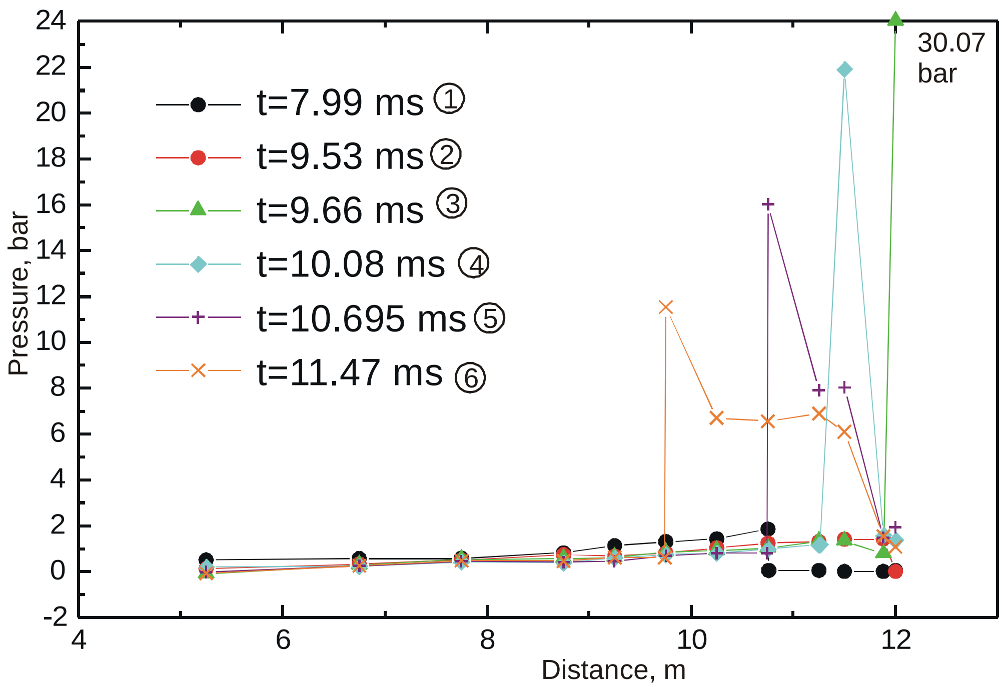

Figure E.1.2-3 Measured pressure profiles along the tube at given times. Initial conditions: 15% hydrogen, pressure in LPS 0.45 bar, pressure in HPS 7.0 bar, Ma = 2.03, velocity of reflected shock wave 1399 m/s

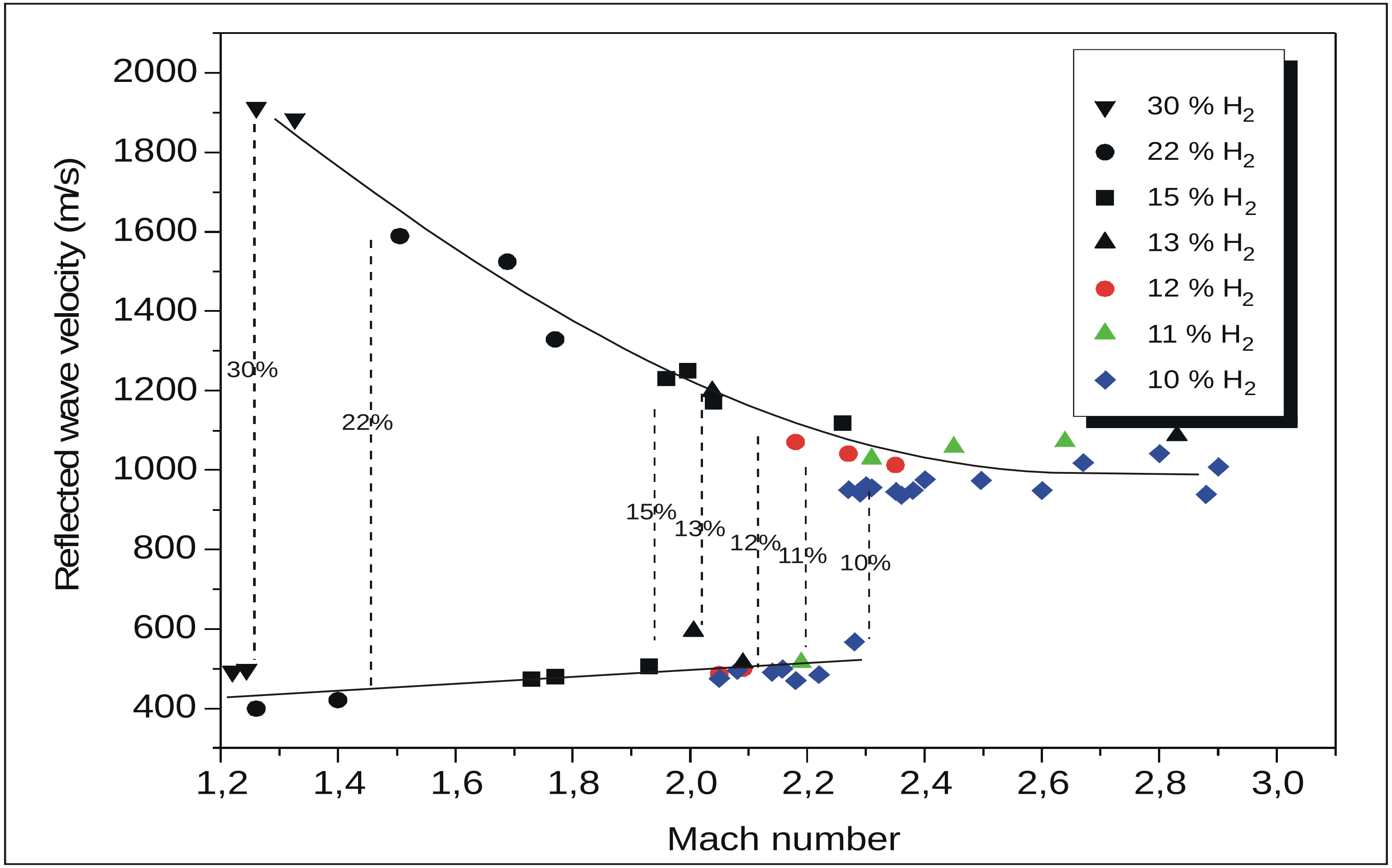

Figure E.1.2-4 Critical Mach numbers for DDT in FZK-tube experiments with shock wave focusing in a conical reflector. The dashed lines indicate the Mach numbers at which a transition occurs from mild ignition (deflagration) to strong ignition (detonation) as a function of the hydrogen concentration in the H_2-air mixture.

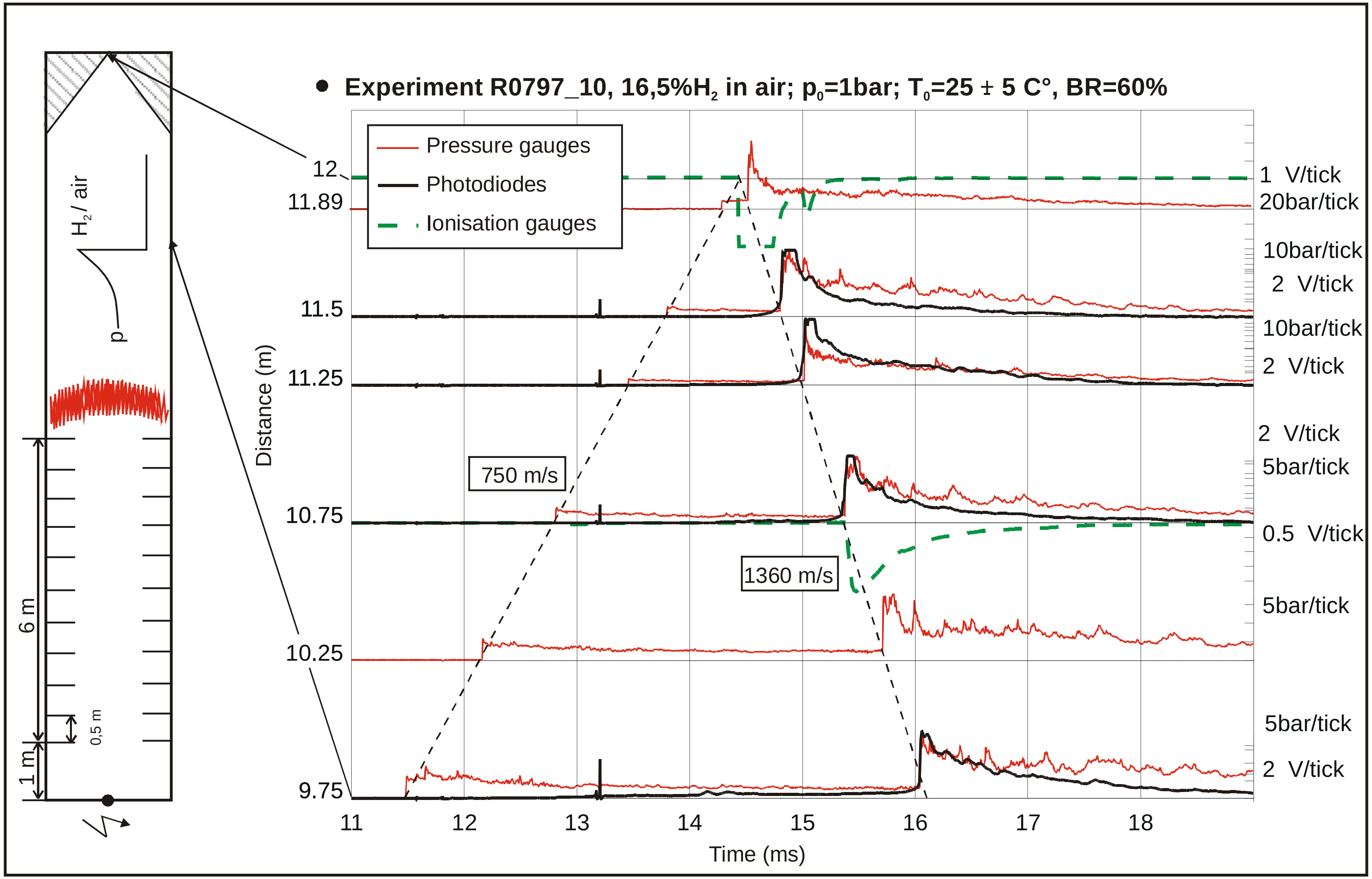

Figure E.1.3-1 Experiment with DDT in the conical reflector induced by focusing of the flame precursor wave

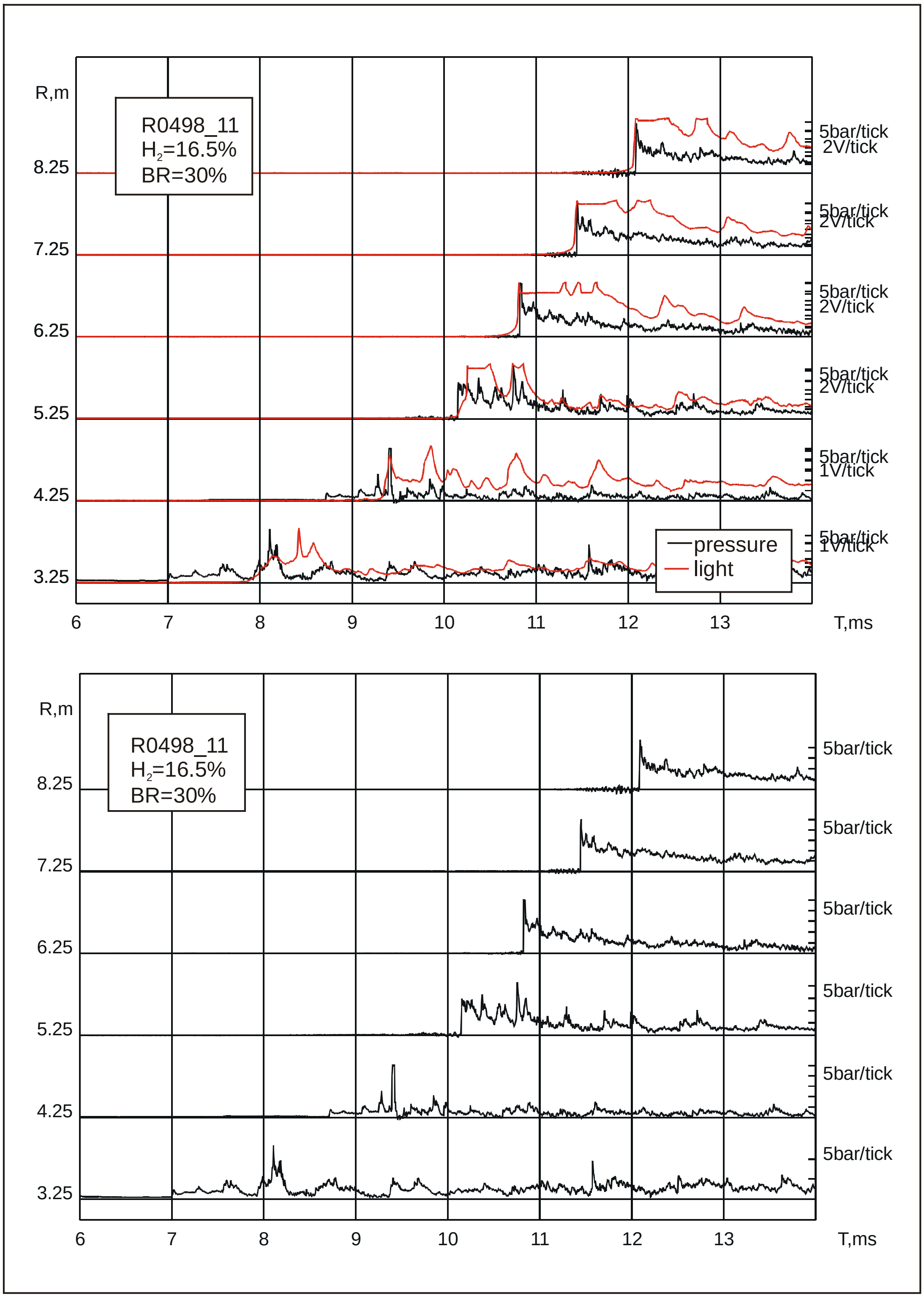

Figure E.1.4-1 Pressure and light signals in an experiment with DDT in or near the turbulent flame brush in the fully obstructed tube. Top: coupling of shock and flame front between the 5.25- and 6.25-m positions. Bottom: change from deflagration to detonation-like pressure amplitudes and shapes.

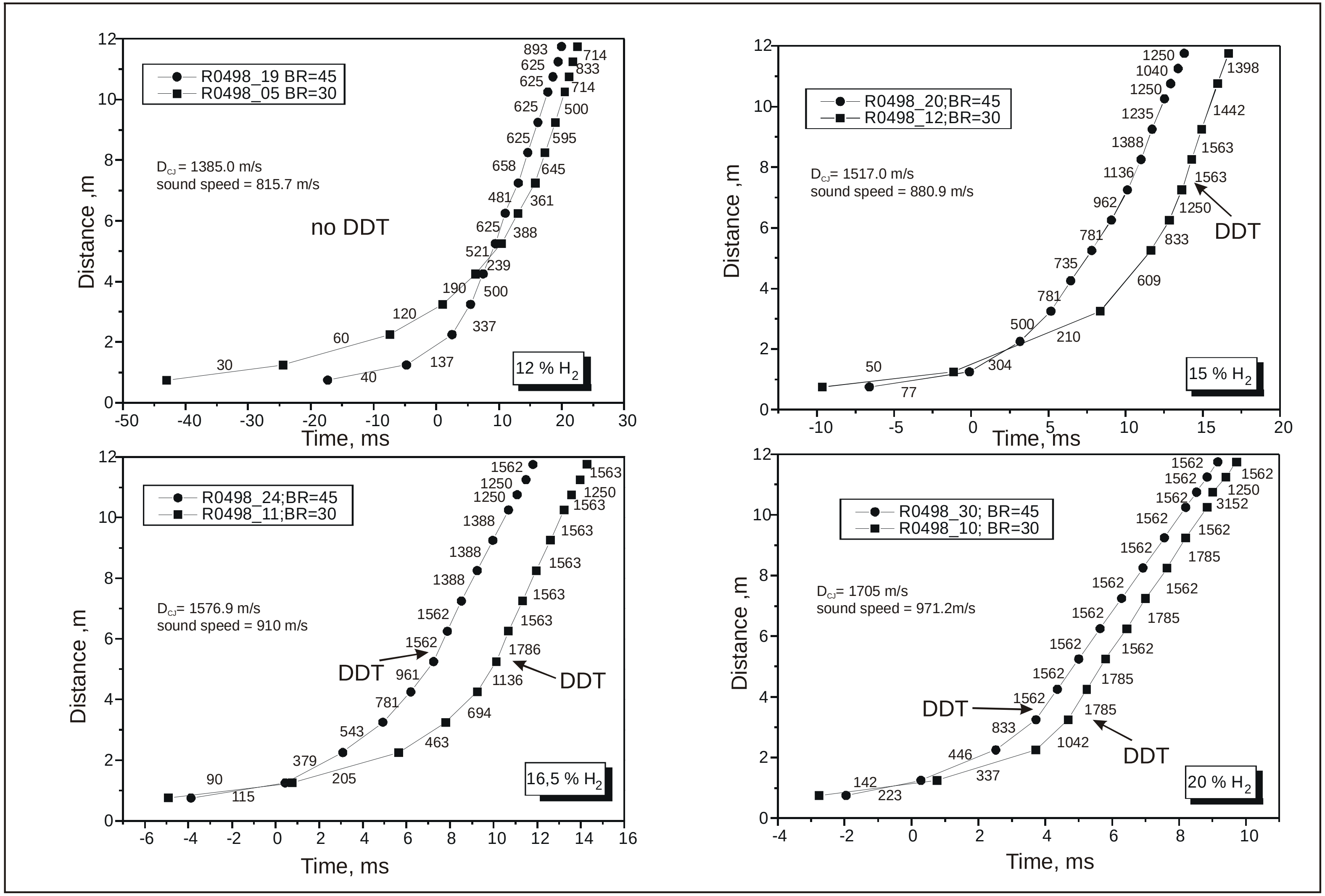

Figure E.1.4-2 Measured local flame speeds in DDT experiments with flames accelerating in a fully obstructed tube geometry. The transition process requires a flame velocity that is close to the isobaric speed of sound in the burnt gas (860 - 1000 m/s).