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Optimizing of Explosion Protection by Design Measures for Special Industrial Applications

Part 1:
Explosion Protection by Design Measures of Bucket Elevators with Explosion Suppression and Chemical Barriers

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Pressure shock resistant design of bucket elevators in combination with explosion suppression and chemical barriers

Abstract

Bucket elevators are widely used for the vertical conveying of combustible bulk materials. Depending on the operating conditions the occurrence of explosible dust/air mixtures as well as potential ignition sources inside the bucket elevator has to be assumed. In many cases measures for the prevention of ignition sources are not sufficient, so additional design features for safety must be taken.
Because there was no sufficient data base to design explosion resistant bucket elevators in combination with explosion suppression, large scale tests were carried out on the test site of BGN and FSA in Kappelrodeck. The tests will be described and the results presented.

1 Introduction

Bucket elevators are conveyors for the vertical transport of bulk materials. They are used in large numbers in various industrial sectors in particular for filling of silos. Depending on the operating conditions and the bulk properties in bucket elevators, there is a risk of dust explosion and explosion propagation into connected plants. If certain effective ignition sources cannot be excluded, additional mitigation measures have to be taken to reduce the impact of such a dust explosion to a safe level [1,2].
Due to the special geometric conditions and the components of the bucket elevators the existing rules for example DIN EN 14 373 "explosion suppression systems" cannot be applied. The effects on both the elongated elevator shafts and the elevator buckets on the course of temporal explosion pressure and flame speed are not known.
However, in order to design safe operational protection systems, this knowledge is crucial and therefore the open questions must be answered by large scale experimental tests.

2 State of the art and objectives

From previous research studies of bucket elevators with explosive bulk materials it is known [3-6], that in case of a fully loaded elevator, ignition of dust/air mixtures and subsequently a flame propagation can also occur. Due to the existing high dust concentration in normal production operations the explosion overpressure is relatively low and generally well below 0.3 bar.
However, the no load operation is very critical because the existing dust deposits gets swirled up by the moving buckets (typical V_F = 3.5 m / s). Under these operation conditions - depending on the bulk properties (K_{St} - value, p_{max}) - high flame speeds and high explosion pressures are to be expected.

Based on the studies of Bartknecht [3] the following requirement was resulted: Chemical barrier protected elevators should be constructed with a pressure shock resistance of 3 bar overpressure in case of conveying burnable dust with an explosion class St1 ($K_{St} \leq$ 200 $bar \cdot m \cdot s^{-1}$). If the lifting height is more than 30 m, for every 30 m an additional chemical barrier is to be installed.
It is to be supposed that the reasons for this strict requirement on explosion shock resistance are based on three factors. Firstly, the fact that a bucket elevator with round elevator legs was used and these elevator types have a relatively large free cross-

sectional area. Secondly, the burnable dust in most of the experiments was dust with a K_{St} – value of 200 bar·m·s^{-1}. And lastly the dust clouds inside the elevator were created by pressurized dust storage containers. The injection and dispersion of dust from pressurized dust storage containers (20 bar) increases the turbulent flow conditions inside the elevator. This leads to an increase of the turbulent burning velocity of the dust/air mixtures and therefore to higher explosion pressures.
However, in practice it is nearly impossible to fulfil the strength requirement for bucket elevators of 3 bar overpressure. Taking into account that the conveyed bulk materials in elevators with a few exceptions have maximum K_{St} – values of 150 bar·m·s^{-1}, the present findings provide an unsatisfactory base for the interpretation of explosion-resistant design related to explosion suppression.

This project pursues the following objectives:

- Optimizing the pressure shock resistance design of bucket elevators with rectangular elevator legs in combination with explosion suppression and chemical barriers.

- Generating of explosive dust/air mixtures by practical operation conditions of bucket elevators.

- Usage of dusts with K_{St}-values of $100 \leq K_{St} \leq 200$ [bar·m·s^{-1}].

- Explosion isolation of connected plants.

In order to achieve the objectives listed above, large scale explosion tests were conducted at the BGN/FSA test plant in Kappelrodeck.

3 Experimental set-up

Following the general practice, for the explosion investigations a twin leg bucket elevator (conveying and return / up and down leg) with rectangular legs was used. With taking additional measures e. g. tension rod in the elevator boot and the use of 10 mm steel plates for the rectangular legs, the explosion resistance of the test elevator was finally increased to 3.5 bar. The length of the elevator legs was about 13 m while the total height of the bucket elevator was about 15 m (see Table 1).
For experimental purposes, the discharge of bulk material at the elevator head was realized through a down pipe (diameter d = 240 mm) connected to the elevator boot, to enable a circuit mode. It was possible to close the inlet opening into the elevator boot. A pipe switch in the down pipe, located near the elevator boot, allowed emptying the bucket elevator.
Regarding flame propagation, the blockage of the elevator legs by the buckets and hence the remaining free cross-sectional area plays an important role. For the tests a modern design elevator with short bucket spacing (130 mm) was chosen with a maximum wall clearance of less than 70 mm. Larger wall distances can support the flame acceleration and therefore cause higher explosion pressures than those measured in the test elevator. The geometric dimensions and specifications are shown in Table 1.

Table 1: Technical data of the test elevator

Total height	15125 mm
Leg size	270 mm x 390 mm
Cross-sectional area (leg)	0.105 m^2
Bucket size	165 mm x 280 mm
Bucket / m	7.5
Bucket volume	~ 3 l (~ 1.8 kg maize starch)
Bucket spacing	130 mm
Wall clearance front	~ 60 mm
Wall clearance side	~ 55 mm
Wall clearance rear	~ 45 mm
Free cross-sectional area	54 %
Conveying capacity	~ 150 t/h grain (bulk weight: 0.75 t/m^3)
Conveying velocity	3.5 m/s

The bucket elevator could be equipped with extinguishing agent containers of explosion suppression systems at the elevator boot and head and additionally with chemical barriers in the elevator legs. In general the extinguishing agent container of the explosion suppression systems and the chemical barriers only differ in the used dispersion nozzle. Chemical barriers usually enter the extinguishing agent over a longer time period than explosion suppression systems. Explosion suppression systems disperse the entire quantity of extinguishing agent as quickly as possible. Due to these measures temporary differences between the initial dispersal of the extinguishing agent and the actual arrival of the flame front at the chemical barrier shall be compensated.

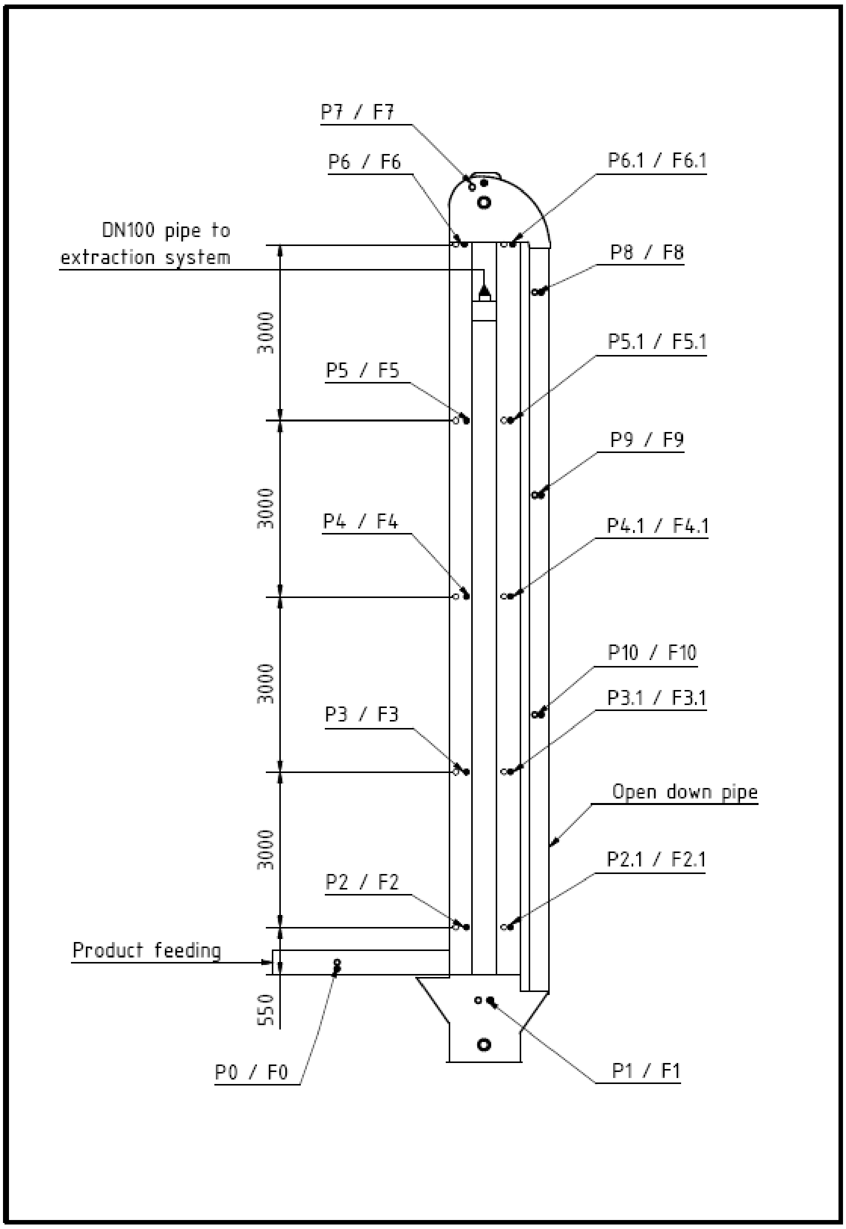


Figure 1: Schematic picture of the bucket elevator with measuring points (P - pressure detector; F – flame detector), possible arrangement of the extinguisher/suppressor and the ignition location.

The experiments described below were conducted with explosion suppression systems and chemical barriers of different manufacturers.
The activation of the protective systems took place by using infrared-sensitive detectors (flame detectors) or pressure detectors. The pressure detectors were always directly installed into the elevator boot and head, while the flame detectors were placed in the elevator legs at a distance of about 0.5 m above the boot or below the head.
In case of pressure detection a distinction was made between static and dynamic detection. At the static pressure detection the exceeding of a defined pressure threshold activates the protection system.
At the dynamic pressure detection however the detection rate of pressure rise is used as a triggering factor. In this case, the activation of the protection system is based on exceeding a predetermined pressure difference, which is measured within a defined time interval ($\Delta p/\Delta t$).

If a defined trigger criterion is reached, the control unit activates the extinguishing agent containers. These are either equipped with pressurized nitrogen and quick opening valves or with gas generators (airbag principle). Sodiumbicarbonat as extinguishing agent was used in the present investigations.

Piezoelectric pressure detectors and flame detectors were installed in defined distances along the elevator legs, at the boot as well as at the head of the elevator.
Figure 1 shows the schematic diagram of the bucket elevator and the locations of the pyrotechnic igniter, the pressure and the flame detectors. Figure 2 shows the exemplary installation of extinguishing agent containers from different manufacturers which allowed the realization of the project.

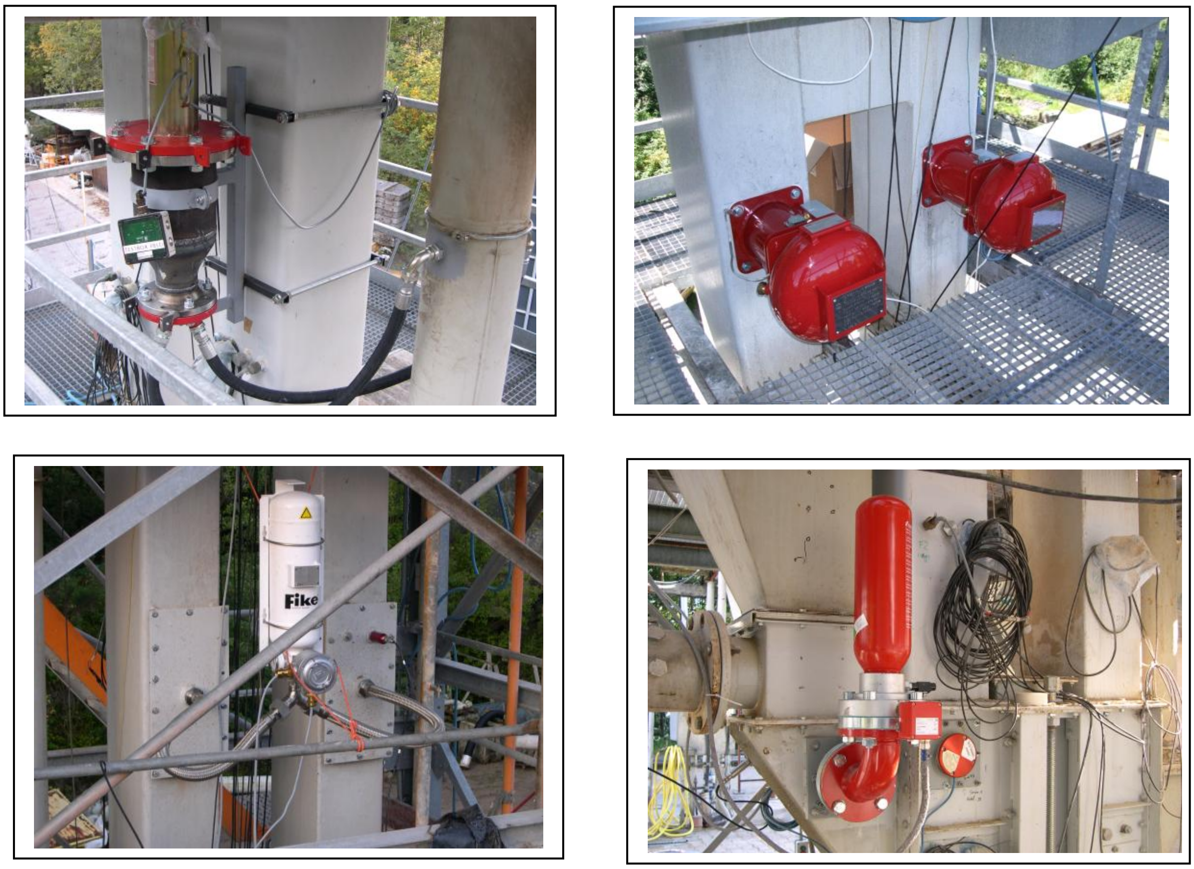


Figure 2: Bucket elevator with extinguishing agent containers from different manufacturers

4 Explosion tests

4.1 Explosion characteristics of the used dusts

The explosion characteristics of the used dusts are shown in Table 2. The given values were determined by standardized dust samples in accordance with the relevant standards [7-10]. As additional information, the dimensionless dusting number S [11] is given, which characterizes the ability of dust cloud formation.

Table 2: Explosion characteristics of the used bulk materials (standardized test sample)

Bulk material	p_{max} **[bar]**	K_{St} **[bar·m·s^{-1}]**	**LEL [g/m³]**	**MIE [mJ]**	**MIT [°C]**	**S**
Wheat flour Typ 550	6.8	109	60	>10 / ≤ 50	380	0.6
Malt dust	8.4	159	60	> 5 / ≤ 10	370	13.2
Maize dust	8.7	204	60	> 4 / ≤ 5	380	10.2

p_{max} - Maximum peak explosion over pressure
K_{St} - Dust specific value
LEL - Lower explosion limit
MIE - Minimum ignition energy (determined with inductivity in the discharge circuit)
MIT - Minimum ignition temperature
S - Dusting number

4.2 Execution of the test

Results and test methods of previous explosion venting tests on bucket elevators could be used for the new research project [5,6]. Figure 3 shows an exemplary explosion test in the scaffolded bucket elevator with explosion pressure venting. In this example there was a pressure venting at the boot, head and in the middle of the legs. There was also an explosion transmission through the dedusting pipe DN 100 (length l = 15 m) to the vented cyclone (right next to the elevator). This fact clearly shows the need of an explosion isolation system.

To achieve the highest possible explosion violence under practical operating conditions, the bucket elevator was loaded with 100 to 200 kg of the selected dust and was run for a defined period of time in circuitry mode by using a down pipe. After emptying the elevator there were only dust deposits left inside. Afterwards the down pipe was closed using a slide gate at the elevator boot.

After having installed the ignition source, the elevator was started again and ran in no-load operation. The running buckets continuously swirled up the available dust deposits inside the elevator and after about 20 seconds the ignition was activated. This ignition delay time was optimized in preliminary tests. There were no relevant differences between the explosion courses perceptible within the time range between 10 s to 60 s, measured from the start of the elevator.

Two different pyrotechnical igniter were used with a total ignition energy of 1 kJ or 5 kJ. In the majority of experiments the ignition location was at the elevator boot where generally the highest explosion pressures occurred [6] and malt dust was used as conveying bulk material. The dust characteristic values of malt dust (see Table 2) covers most of the realistic conveying bulk materials of bucket elevators.

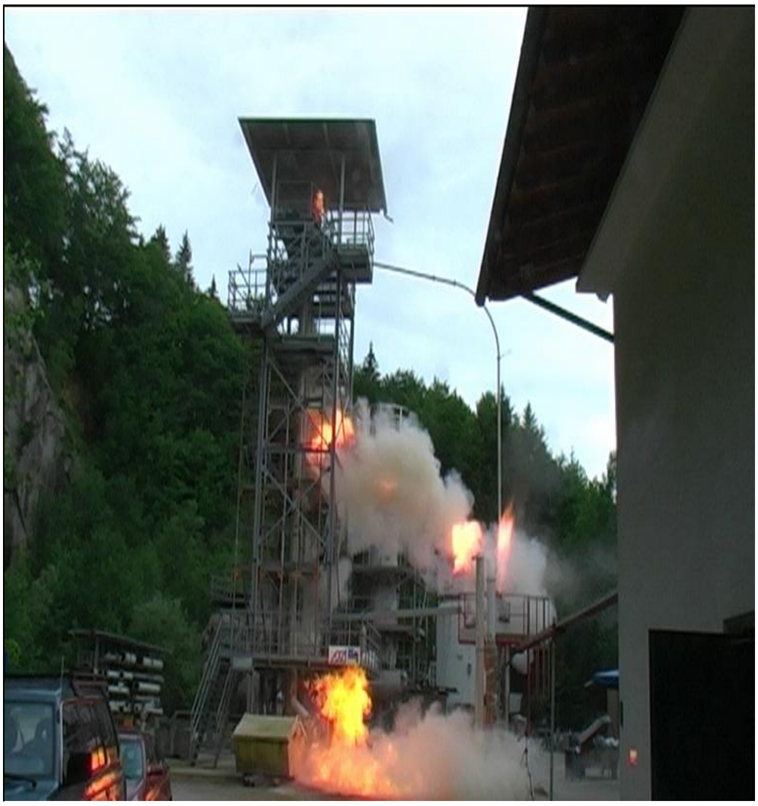


Figure 3: Dust explosion in a vented bucket elevator at the BGN / FSA test plant in Kappelrodeck with explosion transmission through the dedusting pipe DN 100 (length l = 15 m) into a vented cyclone [6].

4.3 Test results

The extinguishing agent quantity used in the different explosion suppression systems and chemical barriers ranged from 2.5 kg to 4 kg per extinguishing agent container. Within this range no relevant differences were found in efficiency and therefore on reduced explosion overpressure either. Sodiumbicarbonat was used in all experiments as extinguishing powder.

For the activation of the explosion suppression systems pressure detectors or flame detectors were used.
The pressure detectors activate the suppression system either by exceeding a defined pressure threshold or a defined rate of pressure rise ($\Delta p/\Delta t$).
If flame detectors were used, the control center was adjusted / manipulated in such a way that triggering the protection system could not be caused by the flame jet of the pyrotechnic igniter

The first explosion tests were conducted by using malt dust and the ignition location was at the elevator boot (Table 3, test C3). At first the extinguishing agent containers were placed only at the elevator boot and head. The activation parameter of the explosion suppression system was set to a static overpressure of 100 mbar. At the moment when the extinguishing agent container got activated, in this experiment, the measured overpressure was (C3) pa = 104 mbar.
Up to this moment the explosion flame could propagate about 3 m inside the elevator leg and finally reached a maximum flame propagation distance of approximately $L_{F,max}$ = 10

m. Thereby a maximum reduced explosion overpressure of $p_{red, max}$ = 1.39 bar was measured in the elevator legs.
The experimental results can be found in Table 3. Related to the elevator legs, only the maximum peak explosion overpressure (measured either in the up or down leg) is shown.
The results of all the installed measuring points can be found in the results tables in the appendix.

For further testing one additional chemical barrier was installed in each leg (up and down leg) at a distance of 6 m, measured from the top of the elevator boot.
The installation distance used in test C7 resulted in a successful extinguishing of the explosion flames. The maximum explosion overpressure 0.87 bar was measured after approximately 3 m in the down leg.
In repeating of test C10 the suppressor was placed in close vicinity of the product inlet. However, at the moment of activation, the flame front propagation distance was already L_F = 5.5 m.
That is the reason why the explosion flames passed the barrier. Therefore a maximum flame front propagation distance of approximately 13 m was measured. The maximum reduced explosion overpressure rose to 1.5 bar in both the elevator boot and in the elevator legs.
The measured explosion overpressure, at the moment of activation, was in all three tests (C3, C7 and C10) within the range of p_{act} = 101 mbar to 104 mbar.

After the tests with static pressure detection depicted before work was continued with dynamic pressure detection. Test D7 was carried out with explosion suppression in the elevator head and boot but no extinguishing barriers in the elevator legs. The triggering criterion was set to a rate of pressure rise of 40 mbar/30 ms. Activation of the protective system finally occurred at a measured explosion overpressure of p_{act} = 90 mbar. However, it was not possible to extinguish the explosion flame in elevator head and boot early enough and consequently flame propagation into the elevator legs was determined over a distance of approximately 13 m.
The maximum reduced explosion overpressure in the elevator legs amounted to $p_{red, max}$ = 2.39 bar in this test. In the elevator boot a reduced explosion overpressure of p_{red} = 1.41 bar was measured.

Table 3: Results of the explosion suppression in the bucket elevator with malt dust, pressure detection

L_F	Flame propagation distance at the time of system activation
$L_{F,max}$	Maximum flame propagation distance
p_{act}	Explosion overpressure at the time of system activation
Distinguishing container	Elevator head (H), Elevator boot (B), Up and down leg (L)
Distinguishing agent	Sodiumbicarbonat
Amount of Distinguishing agent	Per distinguishing container from 2.5 kg to 4 kg

Test No.	Ignition location	Measured values						Suppression system		
		Boot p [bar]	Leg p [bar]	Head p [bar]	Flame L_F [m]	Flame $L_{F,max}$ [m]	p_{act} [mbar]	Setting detection	Extinguishing agent container	Installation distance [m]
C3	B	0.98	1.39	0.93	3	10	104	100 mbar	H B	0
C7	B	0.61	0.87	0.42	2.5	5	103	100 mbar	H L B	6
C10	B	1.5	1.49	0.76	5.5	13	101	100 mbar	H B**	
D7	B	1.41	2.39	1.34	7	13	90	40 mbar/ 30 ms	H L B	6
D8	B	0.45	0.64	0.32	5	7	79	30 mbar/ 100 ms	H L B	6
D10	B	0.83	0.93	0.48	2	6	60	*35 mbar/ 100 ms	H L B	6
D12	H	0.16	0.18	0.17	-	1	40	35 mbar/ 100 ms	H L B	6
D13	H	0.33	0.40	0.35	2	7	67	35 mbar/ 100 ms	H L B	6
H3	B	0.34	0.34	0.13	1	1.5		20 mbar	L B	1.4
H6	H	1.10	2.05	0.30	5	14		20 mbar	H L	1.4
H7	H	0.30	0.58	0.58	3	5		20 mbar	H L	5

* Head: 30 mbar/100 ms and boot: 35 mbar/100 ms

** Installation of the extinguishing agent container in the area elevator boot / product inlet

A significant improvement of the results was achieved after installation of extinguishing barriers in the elevator legs 6 m above the boot and 6 m below the head and optimization of the triggering criterion made simultaneously (from 40 mbar/30 ms before to 30 mbar/100 ms respectively 35 mbar/100 ms). Now activation occurred already at an explosion overpressure of p_{act} = 79 mbar and accordingly 60 mbar (test D8 and D10). The explosion flame reached a maximum flame propagation distance of approximately 7 m. The maximum reduced explosion overpressure was 0.93 bar in the elevator legs

Two further tests (D12, D13) were conducted with the same settings of the detection system, however, the ignition location was changed to the elevator head. In this case a maximum flame propagation distance of 7 m (test D13) was measured as well. The maximum reduced explosion overpressure was only $p_{red,max}$ = 0.4 bar.

Further explosion tests were carried out with static pressure detection and a very low tripping limit of p_a = 20 mbar pressure. The chemical barriers were installed in a mounting distance of only 1.4 m above the elevator boot (test H3). In test H3 the explosion flame was extinguished successfully. The maximum reduced explosion overpressure was $p_{red, max}$ = 0.34 bar both in the elevator boot and elevator legs. The replication of test (H4) showed an increase of the maximum reduced explosion overpressure to $p_{red, max}$ = 0.5 bar. Another test (H6) was carried out with the ignition location placed at the elevator head. In this test, the chemical barriers were installed in each up and down leg with a mounting distance of 1.4 m below the elevator head.
This case, however, showed that the mounting distance was chosen too low. The explosion flame rans over the chemical barrier down to the elevator boot. Therefore, the maximum reduced explosion overpressure reached $p_{red, max}$ = 1.72 bar in the elevator legs and p_{red} = 1.10 bar in the elevator boot.
After having extended the installation distance from 1.4 m to 5 m the explosion flame could be extinguished safely. In this case, the maximum reduced explosion overpressure reached $p_{red, max}$ = 0.58 bar in the elevator head and legs (test H7).

Two additional experiments were carried out with a less violently reacting wheat flour type 550 and with the ignition location placed at the elevator boot (see Table 4).
In this case the installation distance of the chemical barrier was 6 m above the elevator boot and 6 m below the elevator head, at the middle of the elevator legs. The tripping limt was set to an overpressure of 35 mbar. In test C14 the settings of explosion suppression and chemical barrier were successful. The explosion overpressure reached only $p_{red, max}$ = 0.1 bar.
In test C16, there was only a chemical barrier used, while no explosion suppression was installed in the elevator boot or head. In this case, however, the protection system was triggered too late. The explosion flame passed the barrier and reached a maximum flame propagation distance of approximately 13 m. Due to the fact that a less violently reacting wheat flour was used, the maximum reduced explosion overpressure reached only a $p_{red, max}$ = 0.29 bar.

After the explosion tests with pressure detection further experiments were performed with flame detectors for triggering the explosion suppression system and the chemical barrier. Malt dust was used again as bulk material. An additional test was carried out with corn starch (test G9). The results of this test series can be found in Table 5.

Table 4: Results of the explosion suppression in the bucket elevator with wheat flour type 550, pressure detection

L_F	Flame propagation distance at the time of system activation
$L_{F,max}$	Maximum flame propagation distance
p_{act}	Explosion overpressure at the time of system activation
Distinguishing container	Elevator head (H), Elevator boot (B), Up and down leg (L)
Distinguishing agent	Sodiumbicarbonat
Amount of Distinguishing agent	Per distinguishing container from 2.5 kg to 4 kg

Test No.	Ignition location	Measured values						Suppression system		
		Boot p [bar]	Leg p [bar]	Head p [bar]	Flame L_F [m]	Flame $L_{F,max}$ [m]	p_{act} [mbar]	Setting detection	Extinguishing agent container	Installation distance [m]
C14	B	0.1	0.09	0.1	3.5	4	33	35 mbar	H L B	6
C16	B	0.28	0.29	0.26	10	13	32	35 mbar	L	6

With ignition locations placed in the elevator boot (test G3) and elevator head (test G4), the activation of the explosion suppression system was very early. Hence, due to the explosion suppression in the elevator boot or head the explosion flame could propagate less than 1 m into the elevator leg. The explosion flames did not reach the chemical barriers which were installed in a 6 m distance in the elevator legs. The maximum reduced explosion overpressure was just $p_{red,\,max}$ = 0.1 bar.

In test G6 and G8 the ignition location was placed at a distance of 0.5 m and 3.5 m respectively above the upper edge of the elevator boot inside the up leg. Due to this ignition location the detection of the explosion flame by the flame detector happened too late. Apparently, the light intensity was too strongly damped due to the dust and the narrow gap between the elevator buckets and the elevator wall. Therefore the explosion flame passed the chemical barrier. The reduced explosion overpressure rose to $p_{red,\,max}$ = 1.4 bar.
The rapid detection of an incipient dust explosion with infrared-sensitive sensors only seem to be reliable if the flame detectors are installed in the elevator boot and head area, and the ignition location is also placed in the elevator boot or head. From practical experience, this is regarded as the most likely ignition location.

After the successful investigations with malt dust and ignition location at the elevator head and boot, an additional test (G9) was carried out with corn starch. In this test, flame propagation was measured up to approximately 4 m into the elevator leg. The maximum reduced explosion overpressure reached $p_{red,\,max}$ = 0.87 bar.

Table 5: Results of the explosion suppression in a bucket elevator with malt dust and corn starch, flame detection

L_F	Flame propagation distance at the time of system activation
$L_{F,max}$	Maximum flame propagation distance
p_{act}	Explosion overpressure at the time of system activation
Distinguishing container	Elevator head (H), Elevator boot (B), Up and down leg (L)
Distinguishing agent	Sodiumbicarbonat
Amount of Distinguishing agent	Per distinguishing container from 2.5 kg to 4 kg

Test No.	Product	Ignition location	Measured values						Suppression system	
			Boot p [bar]	Leg p [bar]	Head p [bar]	Flame L_F [m]	Flame $L_{F,max}$ [m]	p_{act} [mbar]	Extinguishing agent container	Installation distance [m]
G3	Malt dust	Boot	0.08	0.06	0.06	< 0.5	<1	25	B L	6
G4	Malt dust	Head	0.05	0.07	0.10	< 0.5	< 0.5	9	H L	6
G6	Malt dust	Up leg (0.5 m)	0.95	1.42	0.29	~1	4	49	B L	6
G8	Malt dust	Down leg (3.5 m)	0.45	1.39	0.65	~3	9	74	B L	6
G9	Maize starch	Boot	0.80	0.87	0.20	~1.5	4	92	B L	6

5 Summary and Discussion of Results

The experimental tests on explosion protection of twin leg bucket elevators by means of explosion suppression and extinguishing barriers gave rise to new findings. If the protective systems were activated by static or dynamic pressure detection using well-proven settings from the practical use, the activation was generally late in bucket elevators.

The explosion flames propagated from the elevator boot or head into the elevator legs very fast and passed the extinguishing barriers already before the explosion suppression and the extinguishing barriers were activated.

Therefore the initially chosen installation distances of 6 m above the elevator boot and below the elevator head have to be increased to approximately 8 m for unmodified activation parameters. However, with this longer installation distance it can be estimated from the test results, that a maximum reduced explosion overpressure of $p_{red,\,max}$ = 1.5 bar can be expected for dusts with explosion characteristics up to K_{St} = 150 bar·m·s^{-1}.

The very early flame propagation into the elevator legs, which took place before any explosion pressure could be measured, might be traced back to the special geometrical conditions and installations of a twin leg bucket elevator:

Elevator boot and head are rather small explosion volumes, connected by the two elevator legs. Consequently in case of ignition in the elevator boot or head the combustion gases can expand into the volume of the elevator legs. Elevator inlet and outlet form additional expansion volumes.
A fast complete ignition of the dust cloud inside the elevator boot or head is constricted by the conveyor belt with the buckets, which on the one hand forms a significant spatial obstruction, and on the other hand draws combustion heat from the starting explosion due to the cooling surfaces of the pulley and the metal buckets in particular.
This explains the astonishing long time delays between ignition (t = 0 s) and the beginning of a pressure rise in the elevator boot (Figure 4 at the top). Illustrated by the tests C10 and D7 this time delay amounted to approximately 0.7 s.

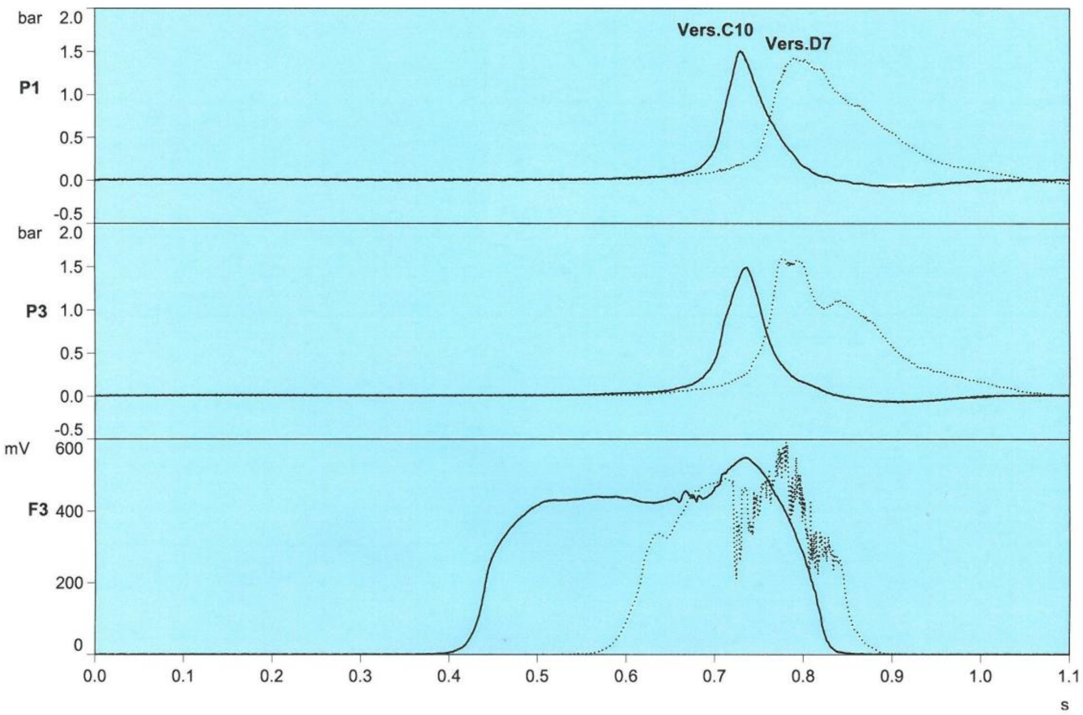


Figure 4: Results from tests C10 und D7: Pressure history inside elevator boot (p1), pressure history inside up leg (p3) in a distance of 3 m above elevator boot, and signals of the flame detector F3 in a distance of 3 m above elevator boot (see table 3). Activation of the igniter happened at time t = 0 s

Looking at the explosion pressure curves and the flame detector signals makes the phenomenon of the early flame propagation very clear. Using results from tests C10 and D7 as an example: In Figure 4 at the top the explosion curves inside the elevator boot (measuring position p_1) and beneath the explosion curves measured inside the up leg (measuring position p_3, approximately 3 m above elevator boot) are shown. At the bottom of Figure 4 finally the signal of the flame detector F_3 installed in parallel to the pressure detector p_3 is displayed.
It can be seen that in test C10 the flame signal on measuring position F_3 reached a first maximum after 0.5 s (measured from ignition). So at that time a first flame front passed measuring position F_3 in the up leg approximately 3 m above the elevator boot. But only

after a further time interval of approximately 190 ms an explosion overpressure of 0.1 bar could be measured in the elevator boot (measuring position p_1).
This time lag was considerably smaller in test D7, but it was still approximately 70 ms in this case.
These observations explain, why settings of the pressure detection systems which are well-proved in many applications did not work properly with a twin leg bucket elevator, so that explosion flames pass the extinguishing barriers and as a result rather high explosion overpressures may arise.

Using pressure detection satisfying results could be achieved only after significant reduction of the minimum triggering level. If the triggering level was reduced to an overpressure of just 20 mbar, extinguishing barriers installed 5 m above the elevator boot or below the elevator head were able to extinguish the explosion flames safely. In this case a maximum reduced explosion overpressure of $p_{red,\ max}$ = 0.58 bar was measured in the elevator legs.

It should be noted at this point that in practical operation the pressure detection can only be set to such low activation pressures, if the detection system has an appropriate interference resistance against vibrations and mechanical shocks. Pressure waves caused by bulk material falling down should not be relevant due to the narrow gaps between the conveyor belt with the buckets and the walls of the elevator legs (according to current design).

Best results could be achieved by means of flame detectors, if the ignition was located in the elevator boot or head. In this case the activation of the extinguishers happened to a very early moment and so the explosion flames could not leave the elevator boot or head at all or only to a maximum length of 0.5 m.

From the test results guidance information regarding installation distances of extinguishing barriers and the required mechanical strength can be derived for twin leg bucket elevators.
In terms of requirements for mechanical strength it can be distinguished between a minimum design pressure p_{a1} for the elevator boot, head and legs up to the installation position of the extinguishing barriers and a lesser design pressure p_{a2} for the legs between the extinguishing barriers (see Figure 5).

From Table 6 the required pressure shock resistance of the twin leg bucket elevator as well as the installation distances for the extinguishing barriers can be taken. The data are indicated as a function of the pressure range within which the extinguishers are activated by means of pressure detectors; information for using flame detectors is given also.

Manufacturer-specific deviations from this guidance information are possible if appropriate evidence is provided.

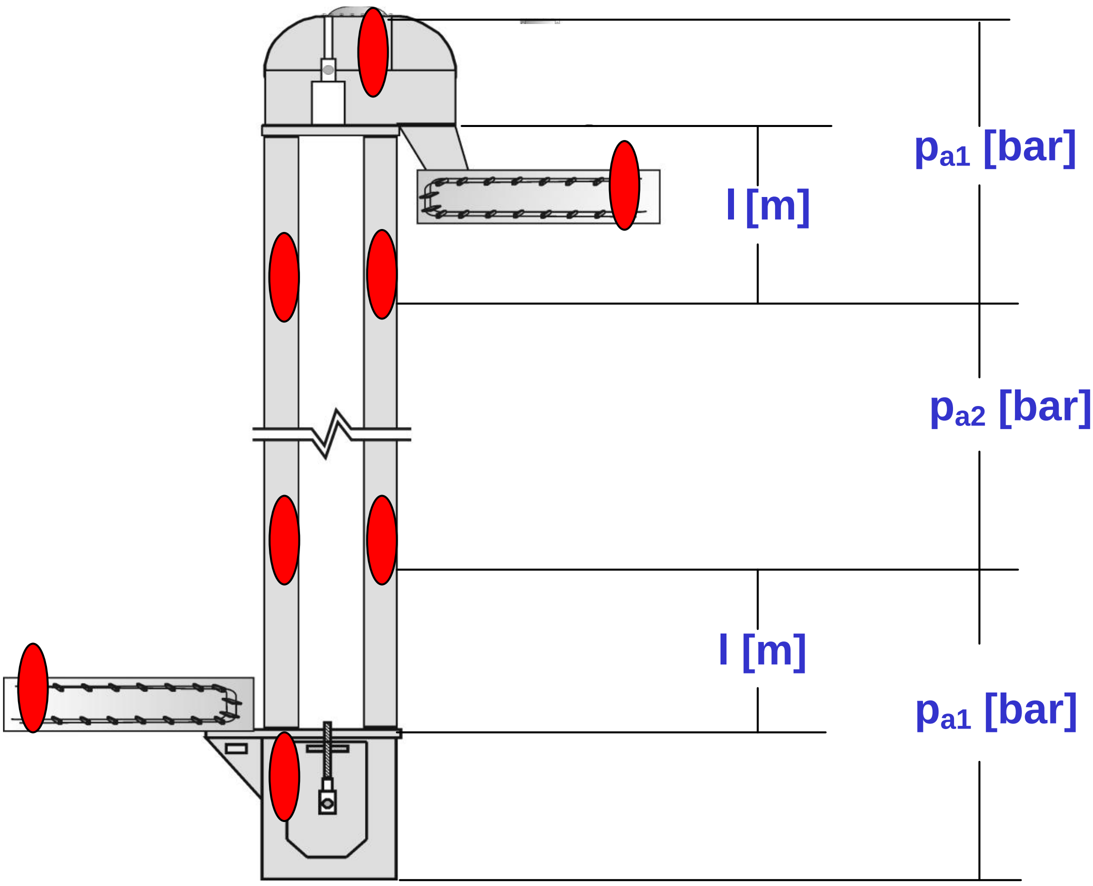


Figure 5: Guidance information to the required mechanical strength of twin leg bucket elevators in combination with explosion suppression and extinguishing barriers as well as to installation distances of the extinguishing barriers (see Table 6).

The information given in Table 6 can be applied under the following conditions:

- Dusts with p_{max} ≤ 9 bar; K_{St} ≤ 150 bar·m·s^{-1}
- Twin leg bucket elevator with rectangular legs
- Metal buckets
- Wall clearance of the buckets on all sides ≤ 70 mm
- Bucket spacing ≤ 280 mm

Table 6: Guidance information to the required mechanical strength of twin leg bucket elevators in combination with explosion suppression and extinguishing barriers as well as to installation distances of the extinguishing barriers (see also Figure 5).

Detection	**Installation distance** **l [m]**	**Required pressure shock resistance p_{a1} [bar]**	**Required pressure shock resistance p_{a2} [bar]**
Pressure detection: Explosion overpressure at the activation moment of the extinguishers: $80 < p_{act} \leq 110$ mbar	8	1.5	1.2
Pressure detection: Explosion overpressure at the activation moment of the extinguishers: $30 < p_{act} \leq 80$ mbar	6	1.0	0.7
Pressure detection: Explosion overpressure at the activation moment of the extinguishers: $p_{act} \leq 30$ mbar	5	0.7	0.4
Flame detection	1.5	0.3	0.2

In the present project only two tests with a dust of $K_{St} \approx 100$ bar·m·s^{-1} (wheat flour type 550) could be carried out (see Table 4). The results suggest that a pressure shock resistance of $p_{a1} \geq 0.3$ bar (overpressure) can be considered as sufficient in the case of pressure detection with an activation pressure range of $p_{act} \leq 110$ mbar and an installation distance of the extinguishing barriers of 8 m. In the case of working with flame detectors by contrast a pressure shock resistance of $p_{a1} \geq 100$ mbar (overpressure) seems to be sufficient.

Note: For bulk material whose fine dust fraction has K_{St}-values ≤ 100 bar·m·s^{-1} no explosion suppression is required irrespective of the length of the elevator, if its pressure shock resistance is ≥ 1 bar (overpressure). This resulted from the research project on explosion venting of twin leg bucket elevators, in which further tests with wheat flour were carried out also without explosion venting (see Table 2) [2, 6].

If bulk material with a fine dust fraction which has K_{St}-values up to 200 bar·m·s^{-1} is conveyed, the bucket elevator should have a pressure shock resistance of ≥ 1 bar (overpressure) and protective systems should be activated by flame detection.

For best functional reliability of the protective system a combination of pressure and flame detection is recommended.

Provided the application limits mentioned in Table 6 are observed, the test results and derived requirements can be applied to twin leg bucket elevators of higher capacity and consequently larger cross section of the legs. Regarding the velocity of the flames escaping the elevator boot or head into the legs no significant deviations are to be expected.
The required quantity of extinguishing agent, however, has to be adapted to the larger volumes of elevator boot, head, and legs.

6 References

[1] VDI 2263 Blatt 8: 2008-12 Staubbrände und Staubexplosionen; Gefahren, Beurteilung, Schutzmaßnahmen; Brand- und Explosionsschutz an Elevatoren, Beuth Verlag , Berlin
[2] VDI 2263 Blatt 8.1: 2011-03 Staubbrände und Staubexplosionen; Gefahren, Beurteilung, Schutzmaßnahmen; Brand- und Explosionsschutz an Elevatoren; Beispiele, Beuth Verlag, Berlin
[3] BARTKNECHT: Explosionsschutz: Grundlagen und Anwendung, S.: 709-715, Springer Verlag, 1993.
[4] Holbrow, P., Lunn, G. A.: Explosion Venting of Bucket Elevators, Stage 2: Final Report (EC/01/50), Health and Safety Laboratory, Buxton, 2001
[5] Vogl, A., Radandt, S.: Explosionstechnische Untersuchungen für den konstruktiven Explosionsschutz von Elevatoren, VDI-Berichte Nr. 2024, Seite 249-266, VDI-Verlag GmbH Düsseldorf 2008
[6] Roser, M., Vogl, A., Radandt, S.: Konstruktiver Explosionsschutz für Elevatoren, Forschungsprojekt F-05-0701, Forschungsgesellschaft für angewandte Systemsicherheit und Arbeitsmedizin (FSA) Mannheim, 2010
[7] DIN EN 14034-1: 2004-12 Bestimmung der Explosionskenngrößen von Staub/Luft-Gemischen – Teil 1: Bestimmung des maximalen Explosionsdrucks p_{max} von Staub/Luft-Gemischen, Beuth Verlag, Berlin
[8] DIN EN 14034-2: 2006-08 Bestimmung der Explosionskenngrößen von Staub/Luft-Gemischen – Teil 2: Bestimmung des maximalen zeitlichen Druckanstiegs $(dp/dt)_{max}$ von Staub/Luft-Gemischen, Beuth Verlag, Berlin
[9] DIN EN 14034-3: 2006-08 Bestimmung der Explosionskenngrößen von Staub/Luft-Gemischen – Teil 3: Bestimmung der unteren Explosionsgrenze UEG von Staub/Luft-Gemischen, Beuth Verlag, Berlin
[10] DIN EN 13821: 2003-03 Explosionsfähige Atmosphären – Explosionsschutz – Bestimmung der Mindestzündenergie von Staub/Luft-Gemischen, Beuth Verlag, Berlin
[11] VDI 2263 Blatt 9: 2008-05 Staubbrände und Staubexplosionen; Gefahren, Beurteilungen, Schutzmaßnahmen; Bestimmung des Staubungsverhaltens von Schüttgütern, Beuth Verlag, Berlin

7 Appendix

7.1 Pictorial documentation

7.2 Results of the measurement

7.3 Pressure- and flame-time histories of selected files

7 Appendix

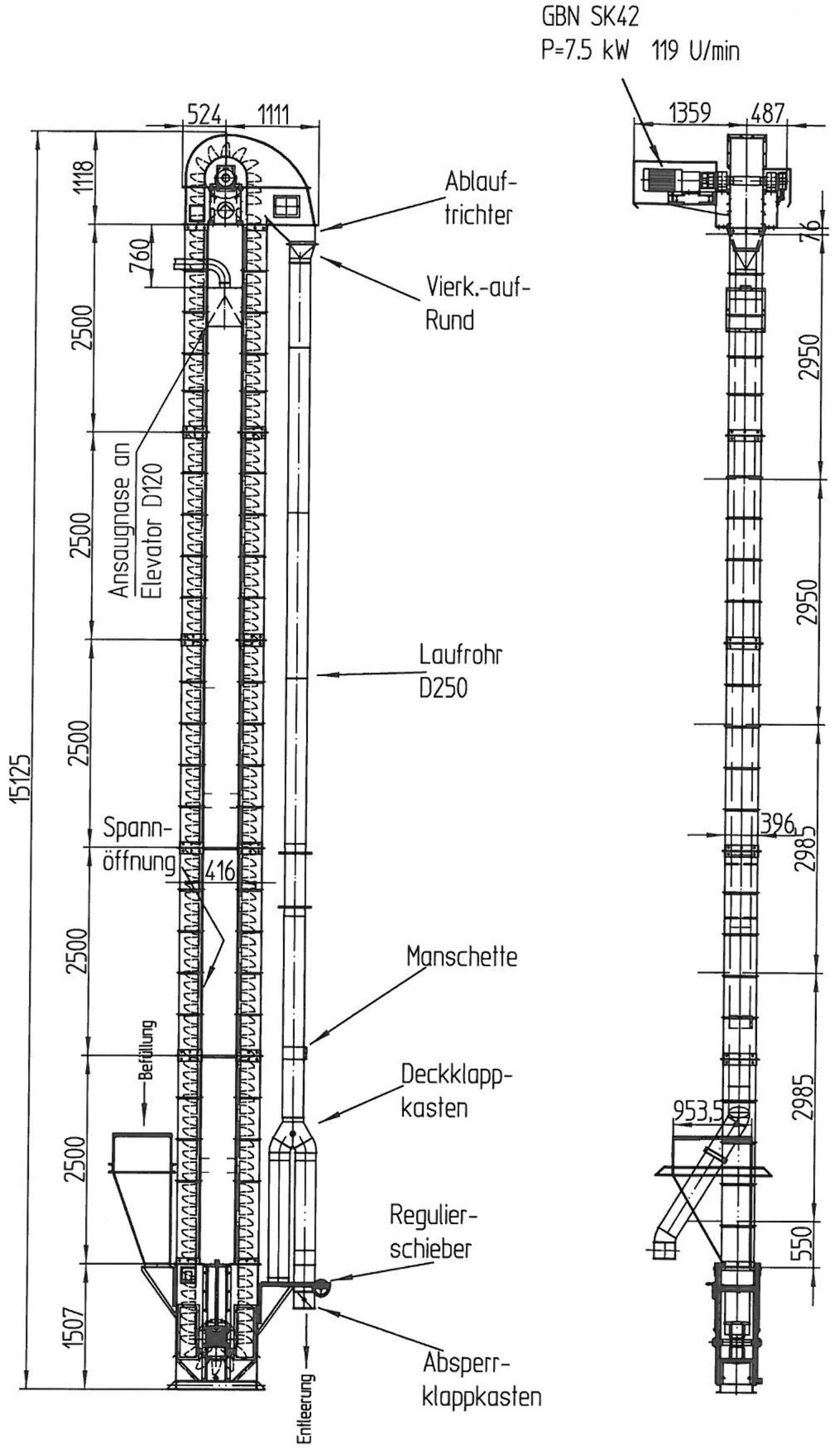
7.1 Pictorial documentation

Figure A1: The test elevator surrounded by scaffolding, on the right the dedusting pipe

Figure A2: Elevator boot with inlet pipe (at the left side) and down pipe (at the right side)

Figure A3: Gate valve at the elevator boot / down pipe

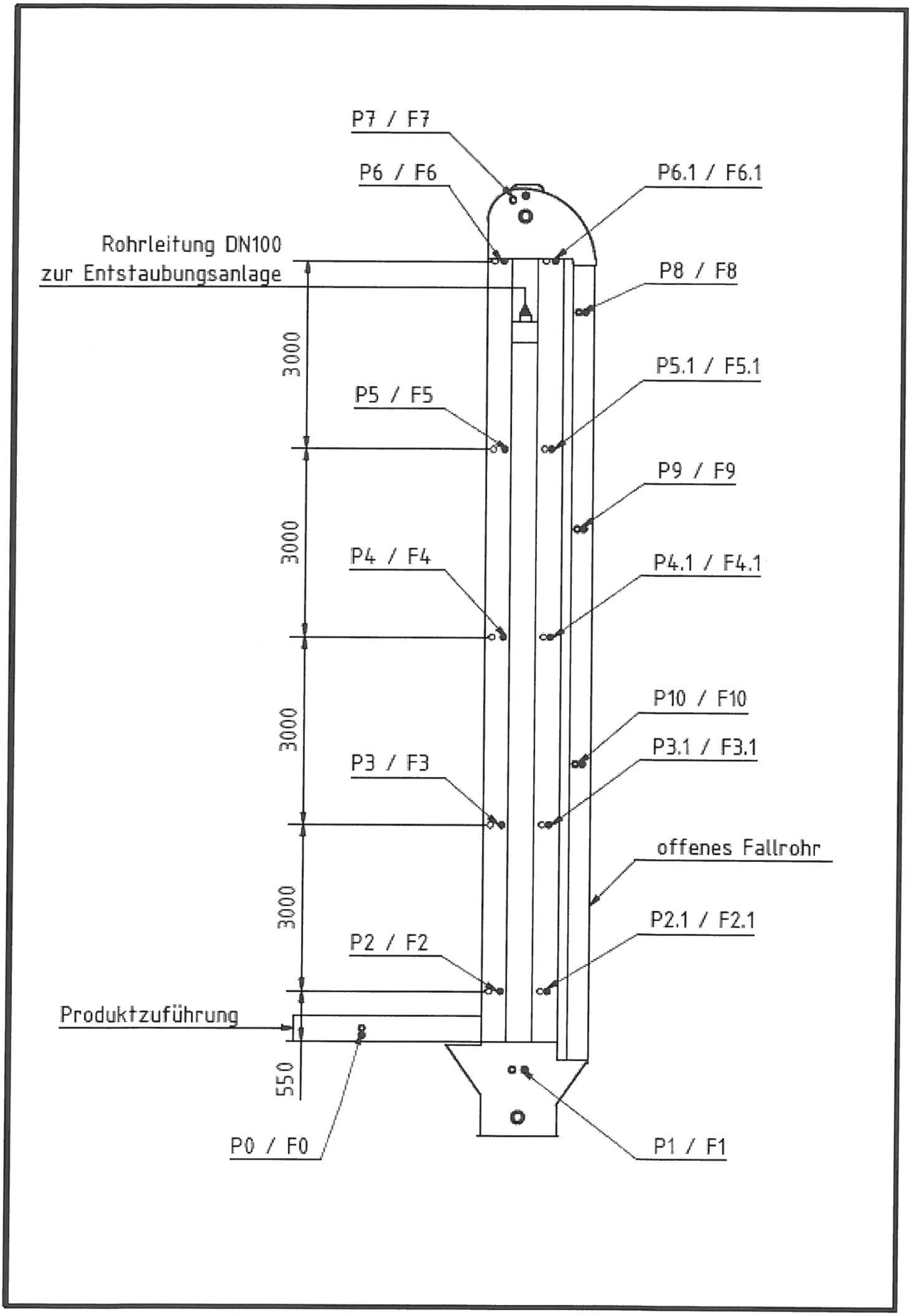
Figure A4: Elevator head



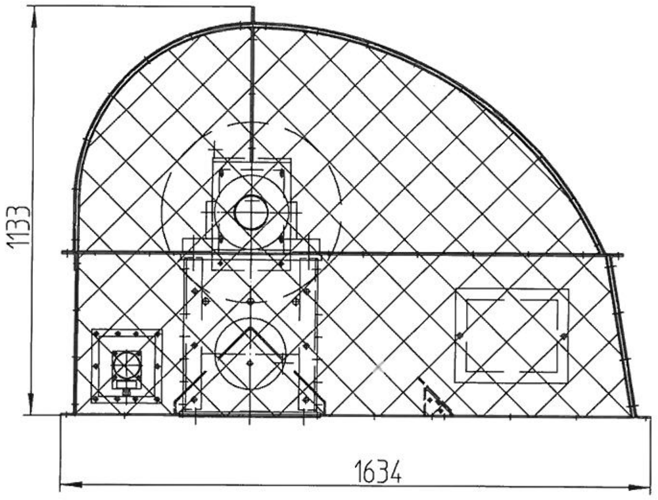
Werkstoff	Freimasstoleranz DIN ISO 2768-mK	Schmidt-Seeger AG	
		Gegenstand: Versuchsaufbau	Maßstab 1:75 1:50
		Zeichnungs-Nr.: 3502_ac_01	

	Tag	Name
Gez.	13-Mar-07	Wittmann
Gepr.		
Norm		

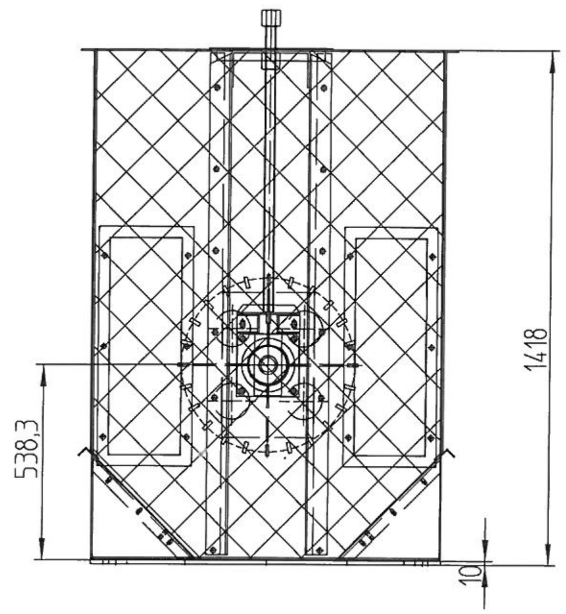
Ausg.	Änderung	Tag	Name



P7 / F7
P6 / F6
P6.1 / F6.1
Rohrleitung DN100
zur Entstaubungsanlage
P8 / F8
3000
P5.1 / F5.1
P5 / F5
P9 / F9
3000
P4 / F4
P4.1 / F4.1
P10 / F10
3000
P3.1 / F3.1
P3 / F3
offenes Fallrohr
3000
P2 / F2
P2.1 / F2.1
Produktzuführung
550
P0 / F0
P1 / F1



507 dm³



480 dm³

Werkstoff				Freimasstoleranz			Schmidt-Seeger	Maßstab
ST				DIN ISO 2768-mK				
					Tag	Name	Gegenstand	
				Gez.	13-Aug-10	Mehringer	Elevatorkopf/fuß 500/315	
				Gepr.			Zeichnungs-Nr.	1:20
Index	Änderung	Tag	Name	Norm			0000_tm_45	

7.2 Results of the measurement

Test No.	Date	Boot	Peak explosion overpressure up leg					Head	Peak explosion overpressure down leg					Outlet	Pressure at activation	Comments
		P1	P2	P3	P4	P5	P6	P7	P6_1	P5_1	P4_1	P3_1	P2_1	P8		
		$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$		
		[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[mbar]	
Ignition location elevator boot (2x 1000 J), malt dust																
C3	10.09.2008	0,981	1,146	1,330	1,324	1,321	0,846	0,927	0,790	0,718	1,165	1,390	1,131	0,418	104	suppression head (2,9 kg) and boot (2,9 kg), detection head: 100 mbar, boot 100 mbar
C7	11.09.2008	0,613	0,643	0,714	0,529	0,418	0,412	0,423	0,385	0,413	0,596	0,875	0,615	0,200	103	suppression head (2,9 kg) and boot (2,9 kg), chemical barrier in both legs (6 m, 8,3 kg), detection head: 100 mbar, boot 100 mbar
C10	11.09.2008	1,498	1,463	1,487	1,434	1,298	0,744	0,757	0,697	0,840	0,848	1,417	1,484	0,371	101	suppression head (2,9 kg) and boot (2,9 kg), chemical barrier in both legs (6 m, 8,3 kg), chemical barrier in inlet pipe (4,48 m, 8,3 kg), detection head: 100 mbar, boot 100 mbar
Ignition location elevator boot (2x 1000 J), wheat flour																
C14	16.09.2008	0,100	0,084	0,092	0,083	0,090	0,073	0,103	0,065	0,081	0,092	0,083	0,067	0,064	33	suppression head (2,9 kg) and boot (2,9 kg), chemical barrier in both legs (6 m, 8,3 kg), detection head: 35 mbar, boot 35 mbar
C16	17.09.2008	0,281	0,286	0,250	0,230	0,253	0,267	0,261	0,263	0,294	0,286	0,223	0,260	0,237	40	chemical barrier in both legs (6 m, 8,3 kg), chemical barrier in inlet pipe (4,48 m, 8,3 kg) detection head: 35 mbar, boot 35 mbar

Test No.	Date	Boot	Flame propagation time up leg					Head	Flame propagation time down leg					Aspiration pipe		Inlet pipe			Outlet pipe		Time at activation
		F1	F2	F3	F4	F5	F6	F7	F6_1	F5_1	F4_1	F3_1	F2_1	F10	F11	F12	F13	F14	F8	F9	
		[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]
Ignition location elevator boot (2x 1000 J), malt dust																					
C3	10.09.2008	714	846	904	946	974				1832	933	891	802								881
C7	11.09.2008	51	345	433								438	286				381	422			402
C10	11.09.2008	48	431	647	696	723						711	614				665				676
Ignition location elevator boot (2x 1000 J), wheat flour																					
C14	16.09.2008	108	411	568									396			443	549	603			547
C16	17.09.2008	21	542	1116	1474	1611			1856	1829	1969				1610	379	1744		1860		1661

Test	Date	Boot	Peak explosion overpressure up leg					Head	Peak explosion overpressure down leg					Outlet	Pressure at activation	Comments
No.		P1	P2	P3	P4	P5	P6	P7	P6_1	P5_1	P4_1	P3_1	P2_1	P8		
		$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$		
		[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[mbar]	
Ignition location: Elevator boot (1x 5000 J)																
D7	25.09.2008	1,41	1,46	1,59	1,85	1,88	1,65	1,34	1,38	2,39	2,36	1,70	1,49	0,69	90	suppression head (4 kg) and boot (4 kg), detection head: 40 mbar / 40 ms, boot 40 mbar / 30 ms
D8	26.09.2008	0,45	0,38	0,53	0,45	0,38	0,31	0,32	0,28	0,37	0,56	0,64	0,52	0,12	70	suppression head (4 kg) and boot (4 kg), chemical barrier in both legs (6 m,4 kg); detection head: 30 mbar / 100 ms, boot 30 mbar / 100 ms
D10	30.09.2008	0,83	0,849	0,817	0,618	0,447	0,441	0,482	0,495	0,548	0,76	0,933	0,901	0,181	60	suppression head (4 kg) and boot (4 kg), chemical barrier in both legs (6m, 4 kg); detection head: 30 mbar / 100 ms, boot 35 mbar / 100 ms
Ignition location: Elevator head (1x 5000 J)																
D12	30.09.2008	0,16	0,162	0,176	0,14	0,134	0,106	0,171	0,116	0,147	0,169	0,158	0,172	0,083	40	suppression head (4 kg) and boot (4 kg), chemical barrier in both legs (6m, 4 kg); detection head: 35 mbar / 100 ms, boot 35 mbar / 100 ms
D13	01.10.2008	0,326	0,328	0,347	0,358	0,398	0,349	0,35	0,341	0,355	0,335	0,297	0,332	0,165	67	suppression head (4 kg) and boot (4 kg), chemical barrier in both legs (6m, 4 kg); detection head: 35 mbar / 100 ms, boot 35 mbar / 100 ms

Test	Date	Boot	Flame propagation time up leg					Head	Flame propagation time down leg					Aspiration pipe		Inlet pipe			Outlet pipe		Time at activation
No.		F1	F2	F3	F4	F5	F6	F7	F6_1	F5_1	F4_1	F3_1	F2_1	F10	F11	F12	F13	F14	F8	F9	
		[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]
Ignition location: Elevator boot (1x 5000 J)																					
D7	25.09.2008		193	599	691	736	769		837	801	722	706	368	763		551	656				700
D8	26.09.2008		54	338	437							419	191			212	347				410
D10	30.09.2008		49	194	327 ?							218	129			102	217				175
Ignition location: Elevator head (1x 5000 J)																					
D12	30.09.2008								141												137
D13	01.10.2008								182		455			198	292						268

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Test	Date	Boot	Peak explosion overpressure up leg					Head	Peak explosion overpressure down leg					Outlet	Pressure at activation	Comments
No.		P1	P2	P3	P4	P5	P6	P7	P6_1	P5_1	P4_1	P3_1	P2_1	P8		
		$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$		
		[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[mbar]	
Ignition location elevator boot (1x 5000 J), malt dust																
G3	26.06.2009	0,075		0,062	0,052	0,049	0,059	0,057	0,051	0,052	0,050	0,050	0,057	0,036	25	suppression boot (2,9 kg) chemical barrier in both legs (6 m, 8,3 kg), chemical barrier in the inlet pipe (4,2 m, 8,3 kg) detection beginning of the legs (0,54 m): optical with time delay of 45 ms
Ignition location elevator head (1x 5000 J), malt dust																
G4	30.06.2009	0,046	0,011	0,054	0,058	0,060	0,074	0,100	0,066	0,064	0,063	0,052	0,060	0,071	9	suppression head (2,9 kg), chemical barrier in both legs (6m, 8,3 kg) detection at the end of the legs (0,54 m): optical with time delay of 45 ms
Ignition location beginning of the up-leg (0,54 m), (1x 5000 J), malt dust																
G6	01.07.2009	0,952	1,043	1,360	1,428	0,788	0,424	0,294	0,243	0,433	0,522	0,744	0,991	0,155	49	suppression boot (2,9 kg), chemical barrier in both legs (6 m, 8,3 kg) detection beginning of the legs (0,54 m): optical with time delay of 45 ms
Ignition location beginning of the up-leg (3,48 m), (1x 5000 J), malt dust																
G8	02.07.2009	0,453	0,645	0,950	1,223	1,388	0,754	0,654	0,523	0,484	0,503	0,400	0,290	0,482	74	suppression boot (2,9 kg), chemical barrier in both legs (6 m, 8,3 kg) detection beginning of the legs (0,54 m): optical without time delay
Ignition location elevator boot (1x 5000 J), dried maize starch																
G9	03.07.2009	0,804	0,729	0,428	0,339	0,208	0,210	0,200	0,212	0,214	0,306	0,455	0,873	0,125	92	suppression boot (2,9 kg), chemical barrier in both legs (6 m, 8,3 kg) detection beginning of the legs (0,54 m): optical with time delay of 45 ms

Test	Date	Boot	Flame propagation time up leg					Head	Flame propagation time down leg					Aspiration pipe		Inlet pipe			Outlet pipe		Time at activation
No.		F1	F2	F3	F4	F5	F6	F7	F6_1	F5_1	F4_1	F3_1	F2_1	F10	F11	F12	F13	F14	F8	F9	
		[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]
Ignition location elevator boot (1x 5000 J), malt dust																					
G3	26.06.2009	0	66										54								45
Ignition location elevator head (1x 5000 J), malt dust																					
G4	30.06.2009						0	0	0					162							45
Ignition location beginning of the up-leg (0,54 m), (1x 5000 J), malt dust																					
G6	01.07.2009	41	0	84									101			50					45
Ignition location beginning of the up-leg (3,48 m), (1x 5000 J), malt dust																					
G8	02.07.2009	144	115	0	111	142	166														114
Ignition location elevator boot (1x 5000 J), dried maize starch																					
G9	03.07.2009	0	39	95									60			0					46

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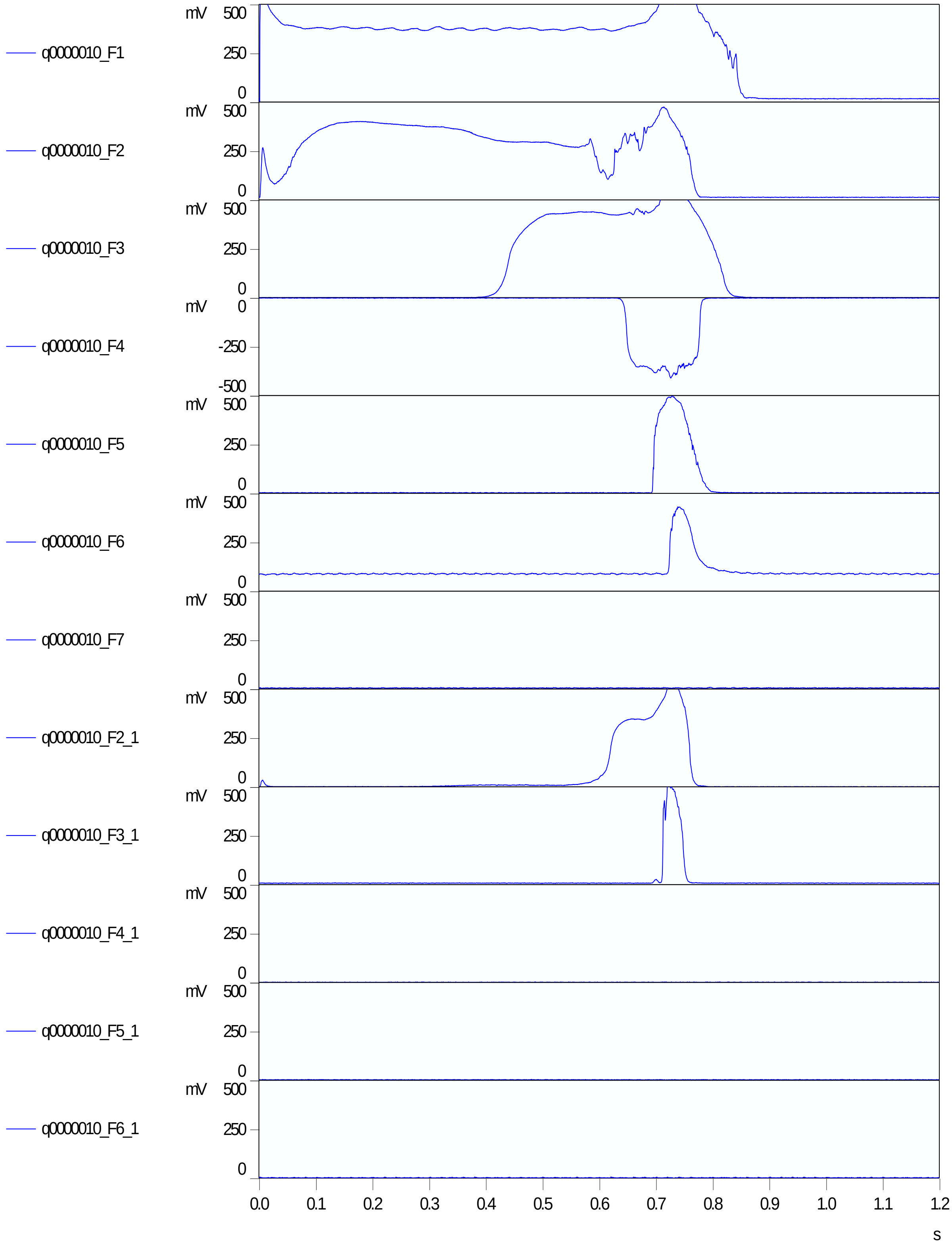
Test No.	Date	Boot	Peak explosion overpressure up leg					Head	Peak explosion overpressure down leg					Outlet	Pressure at activation	Comments
		P1	P2	P3	P4	P5	P6	P7	P6_1	P5_1	P4_1	P3_1	P2_1	P8		
		$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$	$p_{red,max}$		
		[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[bar]	[mbar]	
Ignition location elevator boot																
H1	20.07.2009	0,318	0,211	0,184	0,159	0,128	0,101	0,105	0,110	0,116	0,067	0,163	0,272	0,090		malt dust (1 x 5000 J) suppression boot (2,5 kg), chemical barrier in both legs (1,40 m, each 2,5 kg)
H3	21.07.2009	0,342	0,336	0,202	0,165	0,118	0,133	0,127	0,120	0,133	0,108	0,172	0,335	0,082		malt dust (1 x 5000 J) suppression boot (2,5 kg), chemical barrier in both legs (1,40 m, each 2,5 kg)
H4	22.07.2009	0,454	0,209	0,204	0,169	0,152	0,129	0,128	0,131	0,160	0,179	0,233	0,499	0,094		malt dust (2 x 1000 J) suppression boot (2,5 kg), chemical barrier in both legs (1,40 m, each 2,5 kg)
H5	23.07.2009	0,191	0,280	0,165	0,215	0,265	0,268	0,271	0,271	0,269	0,243	0,205	0,180	0,203		wheat flour (2 x 1000 J) suppression boot (2,5 kg), chemical barrier in both legs (1,40 m, each 2,5 kg)
Ignition location beginning of the leg/elevator boot (1 x 5000 J), malt dust																
H2	20.07.2009	0,312	0,305	0,157	0,141	0,115	0,107	0,107	0,113	0,125	0,133	0,140	0,287	0,088		suppression boot (2,5 kg), chemical barrier in both legs (1,40 m, each 2,5 kg)
Ignition location elevator head (2 x 1000 J), malt dust																
H6	28.07.2009	1,101	0,860	0,850	0,524	0,326	0,279	0,303	0,380	0,943	1,559		1,721	0,118		suppression head (2,5 kg), chemical barrier in both legs (1,40 m, each 2,5 kg)
H7	29.07.2009	0,297	0,281	0,280	0,346	0,562	0,582	0,577	0,578	0,533	0,334	0,275	0,290	0,451		suppression head (2,5 kg), chemical barrier in both legs (5 m, each 2,5 kg)

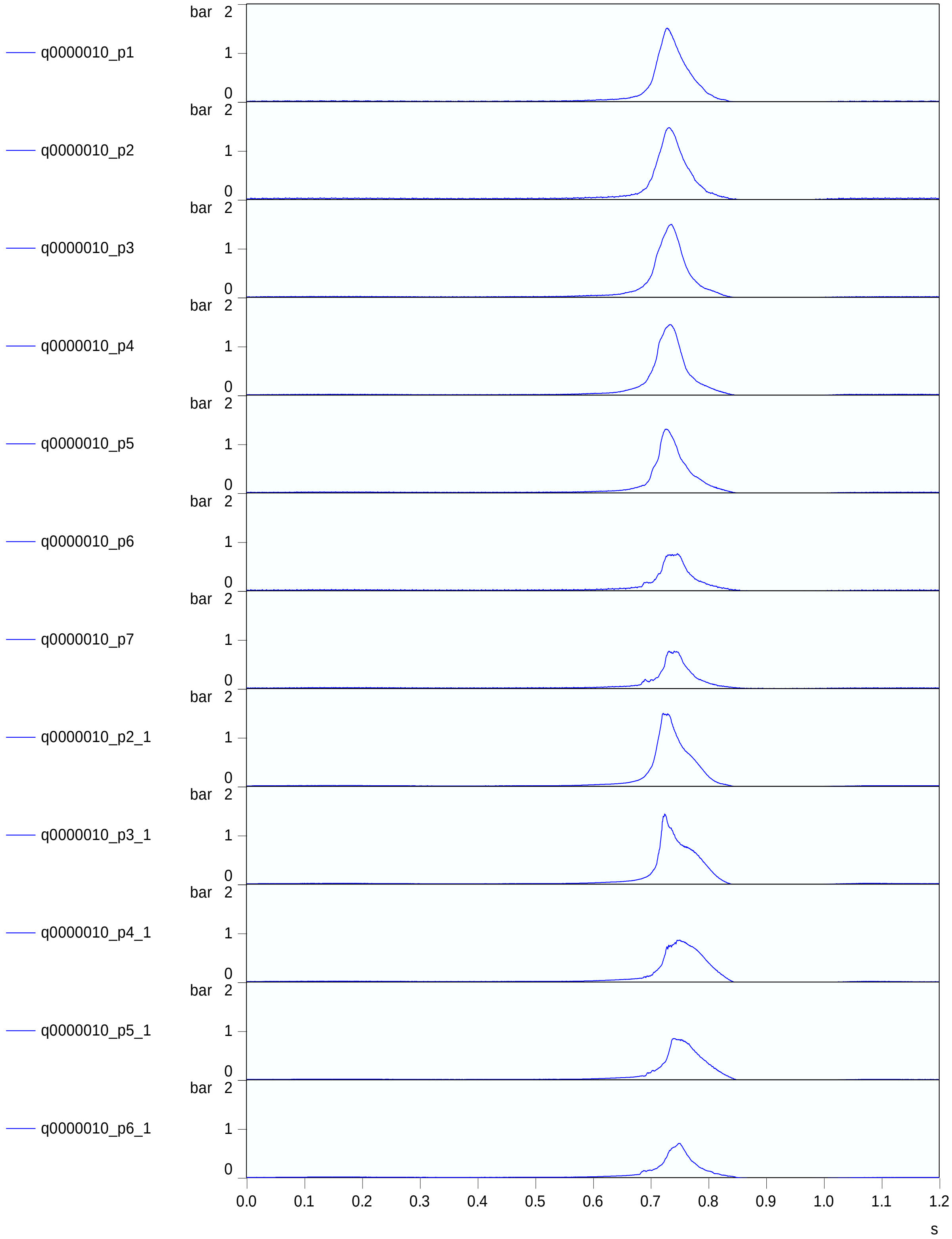
Test No.	Date	Boot	Flame propagation time up leg					Head	Flame propagation time down leg					Aspiration pipe		Inlet pipe			Outlet pipe		Time at activation
		F1	F2	F3	F4	F5	F6	F7	F6_1	F5_1	F4_1	F3_1	F2_1	F10	F11	F12	F13	F14	F8	F9	
		[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]	[ms]
Ignition location elevator boot																					
H1	20.07.2009		73																		
H3	21.07.2009		64													135					
H4	22.07.2009		65										116				127				
H5	23.07.2009		178	542	1067	1212	1275	1342	1395	1437	1553			1278		1145	1260	1297	1411	1449	
Ignition location beginning of the leg/elevator boot (1 x 5000 J), malt dust																					
H2	20.07.2009																				
Ignition location elevator head (2 x 1000 J), malt dust																					
H6	28.07.2009			2181	1993	1264				1162	1312	1339	1359	836					1059	1245	
H7	29.07.2009					585			144	520				442					543		

7.3 Pressure- and flame time histories of selected tests

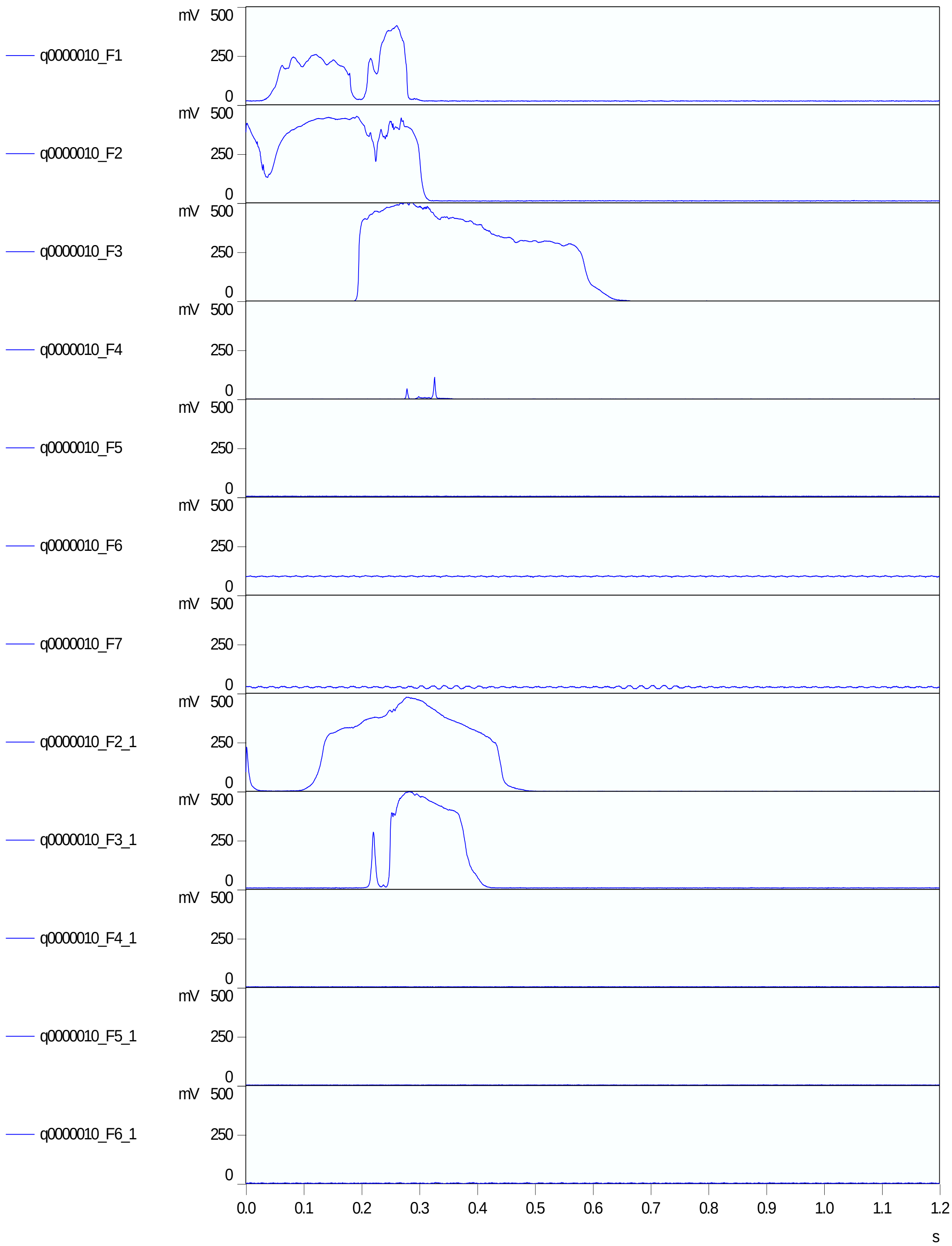
Test C10_flame



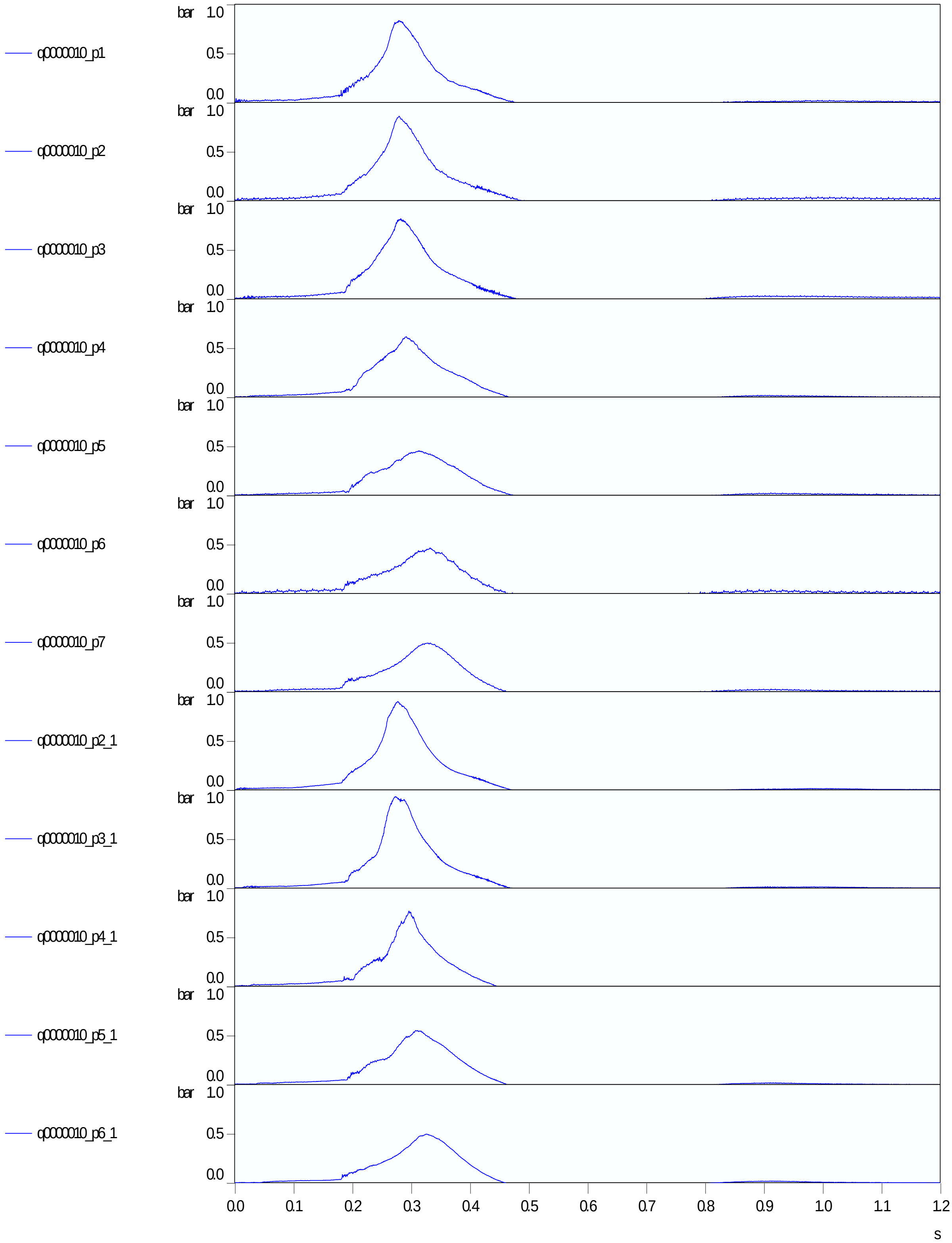
Test C10_pressure



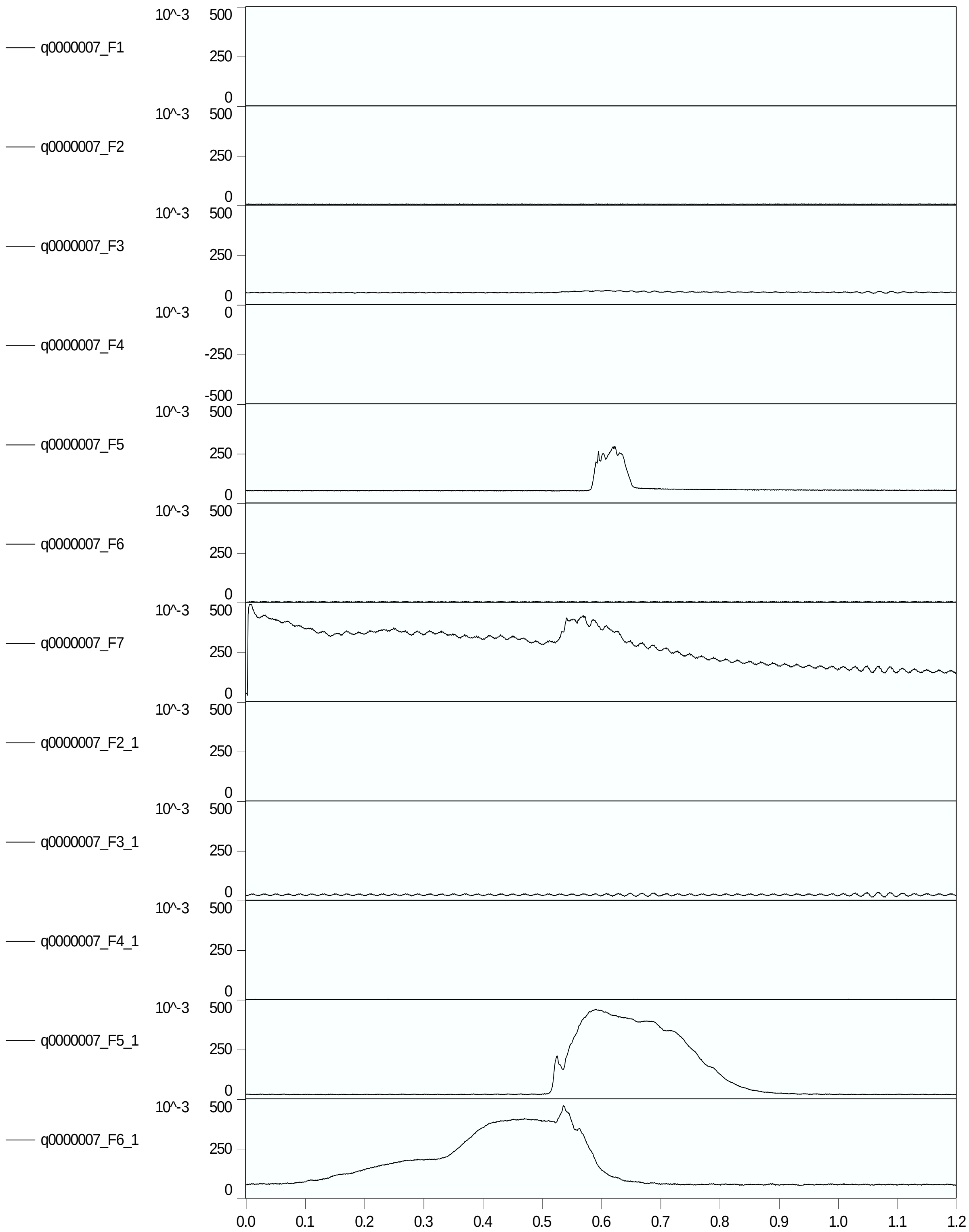
Test D10_flame



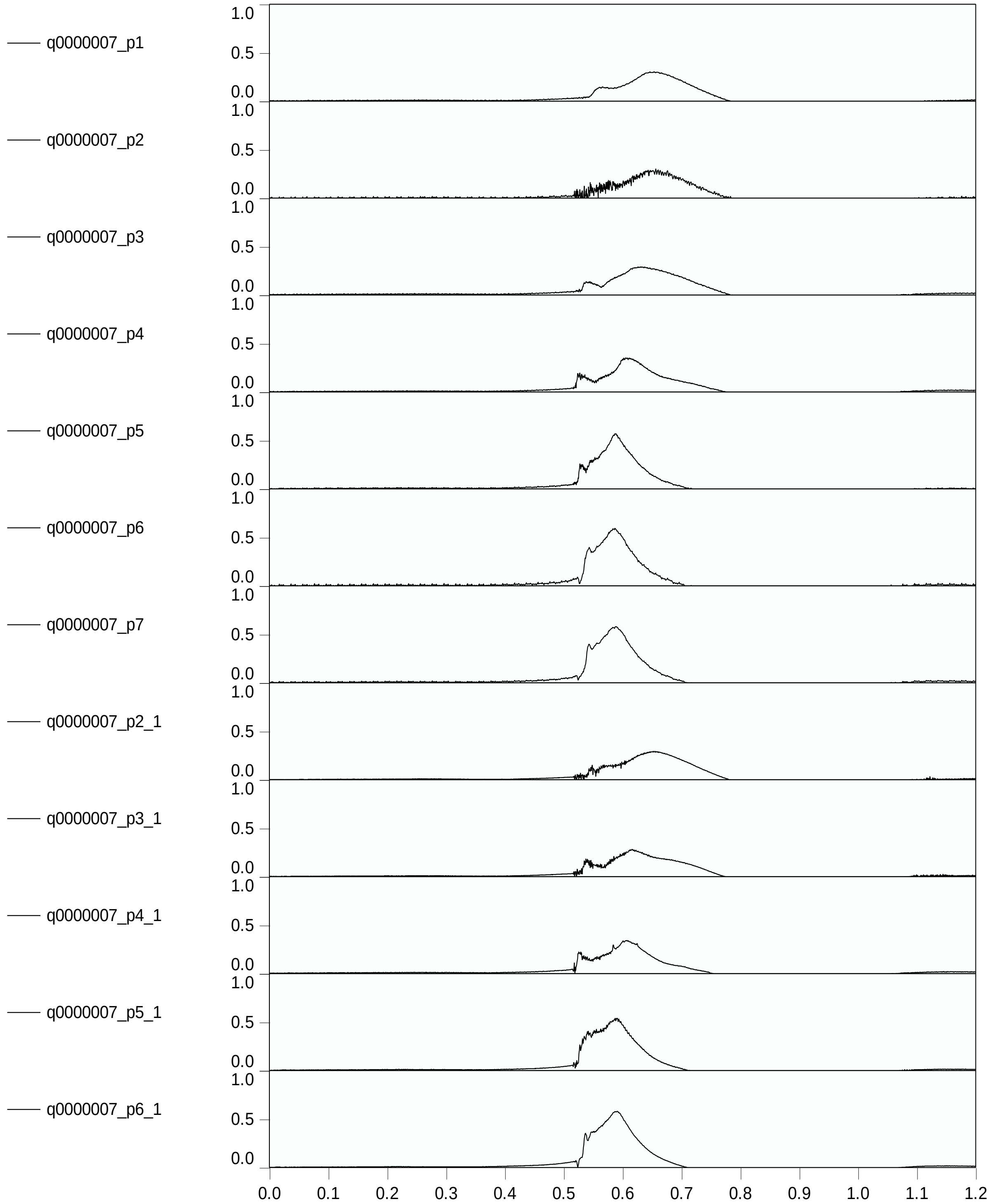
Test D10_pressure



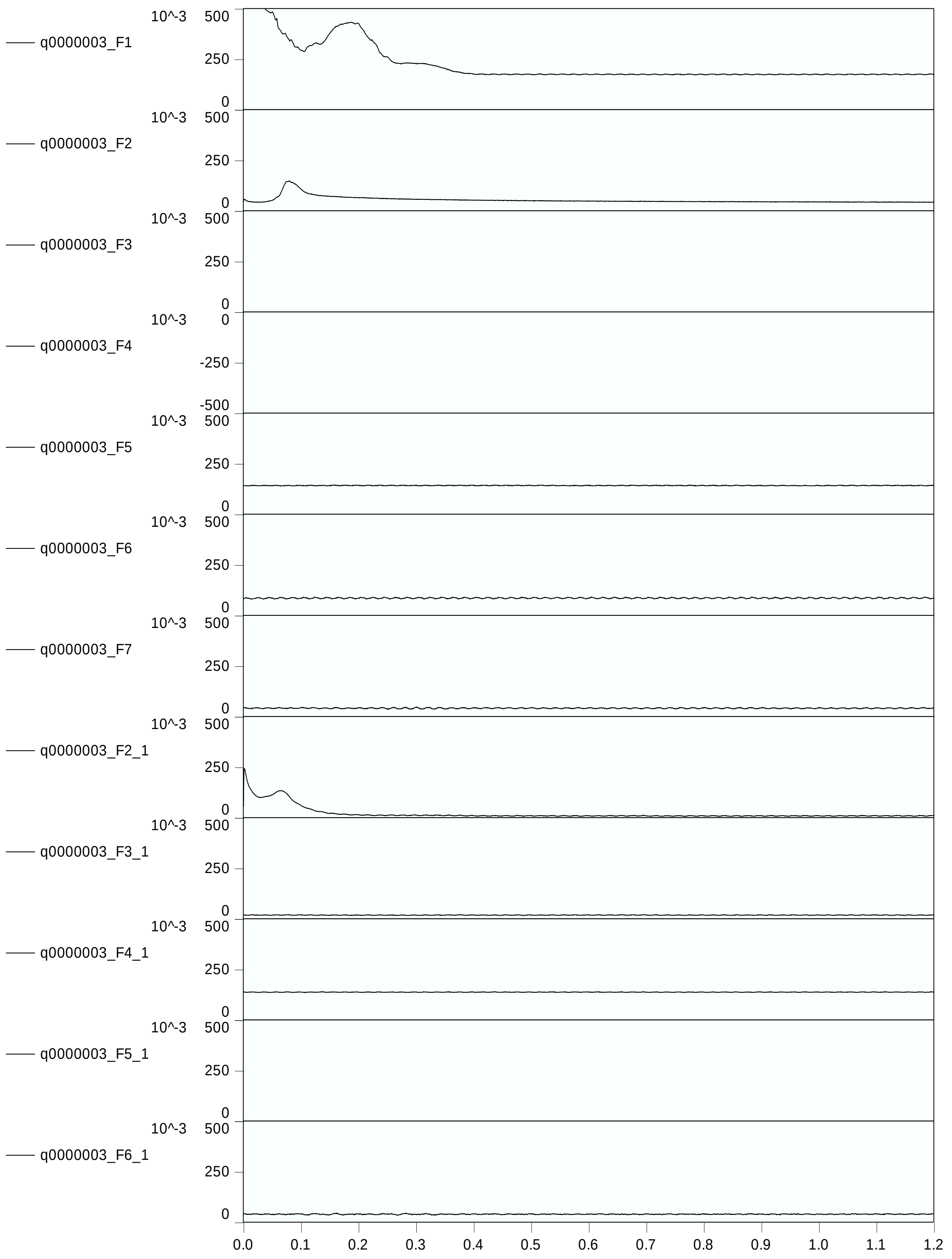
Test H7_flame



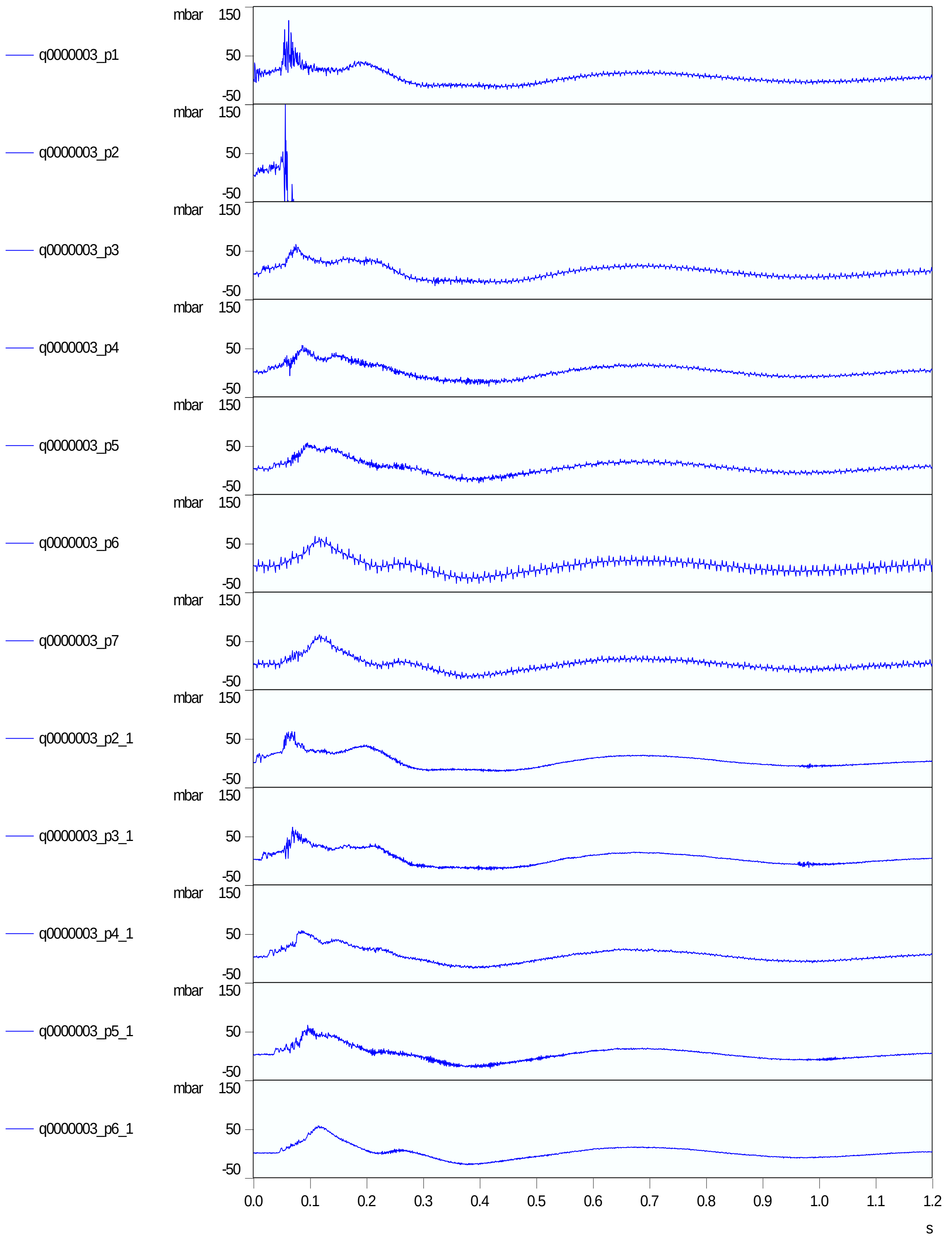
Test H7_pressure



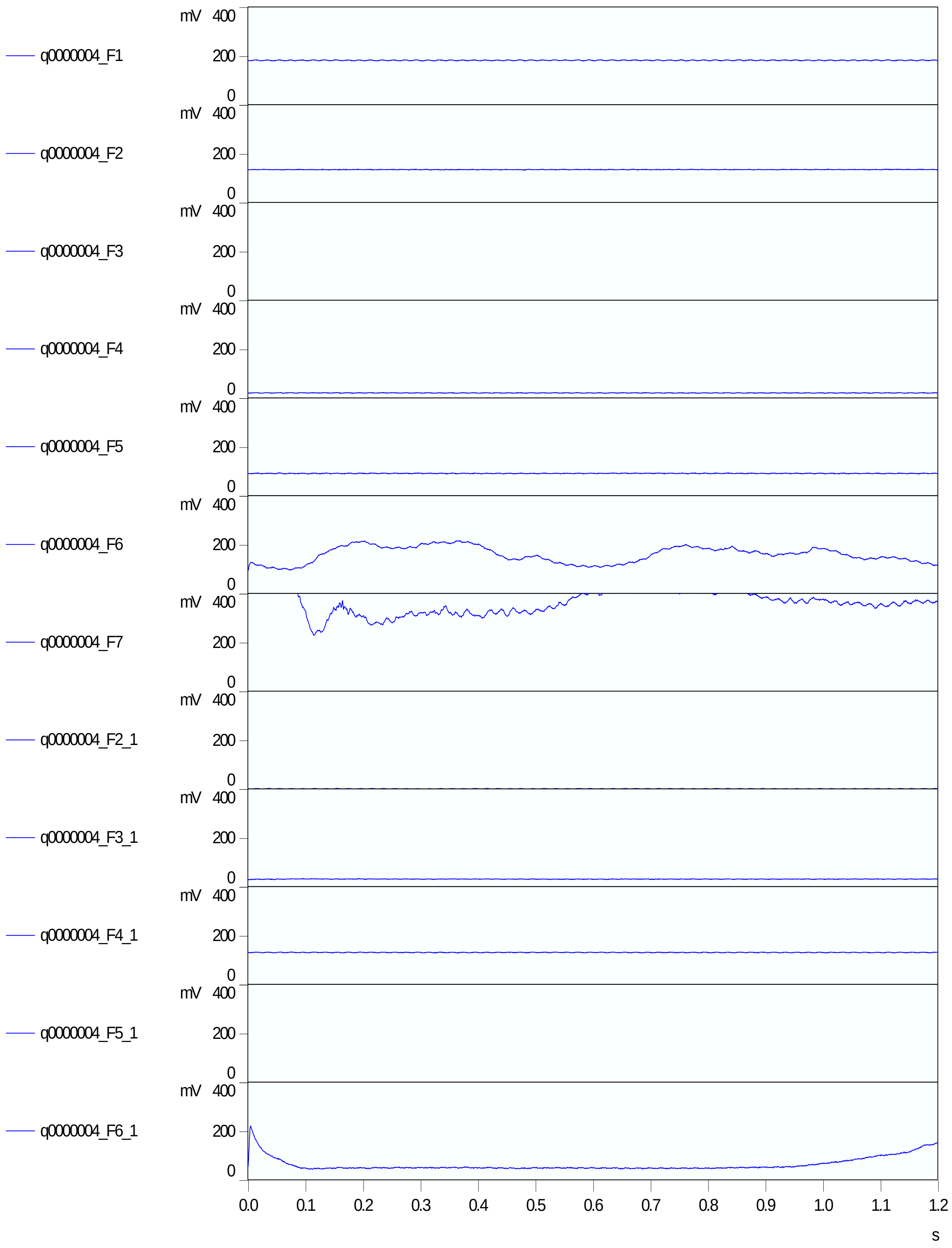
Test G3_flame



Test G3_pressure



Test G4_flame



Test G4_pressure