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Analysis of structural response measurements - Phase 3B Spadeadam

Prepared by **CREA Consultants Limited**
for the Health and Safety Executive

OFFSHORE TECHNOLOGY REPORT

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EXECUTIVE SUMMARY

The Phase 3b tests performed at Spadeadam in September 1999 incorporated a number of sensors to enable the measurement of local stress time histories and structural response in addition to the sensors traditionally used to characterise the explosion loads.

The major technical content has been presented in this main report and three appendices.

The main report provides a general overview of the work and presents an overall discussion of the main results. The measured pressure traces are found to contain a high frequency component of uncertain origin. Appendices A and B deal with the identification of the source of this noise and rigorous methods for its removal. Appendix C deals with the interpretation of the strain gauge, accelerometer and displacement transducer measurements from a global structural point of view and uses the response results for a cylindrical obstacle at the vent to estimate vented gas velocities.

Appendix A 'Identification of Time-history Noise', presents an examination of the sources of the noise recorded with the overpressures from the explosion tests on the Spadeadam test rig.

Various potential sources have been identified: the detonator chord, background noise originating from the data acquisition system and structural response to the explosion. The results of this work show that the most likely source of the noise is the local response of the structure, which causes the pressure transducers to measure additional overpressure. An important conclusion is that the additional high frequency components of overpressure can and should be removed.

Appendix B 'Cleaning of Recorded Time Histories', discusses the cleaning of the time histories, and describes a semi-automated cleaning technique. The appendix demonstrates that the recorded time-histories can be effectively cleaned giving greatly reduced headline overpressures and far fewer points needed to characterise the load time history. The use of the cleaned time histories will make accurate structural response analyses much more efficient.

Appendix C 'Global Response and Measurement of Vented Gas Velocities', looks at the global and local structural responses and the measurement of gas velocities.

The objectives of this part of the work were:

- The measurement of vented gas velocities and dynamic pressures on obstacles in the vent area.
- The measurement of (low frequency) global structural response, in particular out of balance venting loads.

Estimates have been made of the peak venting velocity but confirmation will depend on information being supplied relating to flame arrival time. This value should be compared with that obtained from explosion simulation.

Monitoring of the structure to determine global response has shown that the response is fully dynamic. The damping in the structure has been identified and indicates that energy is being dissipated at the bolted connections. The displacement transducer measurements have been made useable by the incorporation of accelerometers on their support structures.

The full loading pattern will need to be known before a response simulation of the test rig can be performed. A full explanation of all the results will require a finite element model of the rig to be generated and the loading applied to the model. A dynamic linear analysis will be sufficient to determine the global response.

1. INTRODUCTION

1.1. UNDERLYING PURPOSE OF THE WORK

The overpressure time histories recorded from the full-scale testing at Spadeadam are characterised by the expected profile of the positive and negative overpressure phases and an overlying high frequency record. This additional overpressure results in predicted overpressures from the tests that are excessive, and in some cases unrealistic.

This document deals with the identification of the source of this noise and rigorous methods for its removal. The strain gauge, accelerometer and displacement transducer measurements are interpreted from a global structural point of view in Appendix C. The response results for a horizontal cylindrical obstacle at the vent have been used to estimate vented gas velocities.

To examine the possible sources of the noise and to examine global response, CREA Consultants located pressure transducers, strain gauges and accelerometers and displacement transducers on the structure for the September 1999 testing. The locations of these additional transducers are presented in Section 2.

1.2. IDENTIFICATION OF NOISE

The noise seen on the overpressure recordings is intuitively extraneous. However, to legitimately remove the noise it is necessary to identify the source and demonstrate that it is not a part of the developing explosion. This work identifies the source of the noise and validates its removal.

1.3. STRUCTURAL RESPONSE

The objectives of this part of the work were:

- The measurement of vented gas velocities and dynamic pressures on obstacles in the vent area

- The measurement of (low frequency) global structural response.

These objectives have been achieved as far as possible, but confirmation of peak venting velocities will depend on information being supplied relating to flame arrival time. Estimation of out of balance venting loads would require a finite element response analysis which was not part of the final scope. Not all of the strain gauge measurements were supplied to the project.

1.4. DOCUMENT ROADMAP

To separate the topics discussed in this work, the major technical content has been presented in this main report and three appendices.

The main report, provides a general overview of the work and presents an overall discussion. Each of the three appendices presents a detailed discussion of the results.

Appendix A examines the likely sources of the noise on the recordings to identify structural response tot he explosion as the most likely cause. The identification of the source gives validity to the cleaning of the recordings.

Appendix B discusses the cleaning of the time histories, and describes a semi-automated cleaning technique. The appendix demonstrates that the recorded time-histories can be effectively cleaned.

Appendix C looks at the global and local structural responses; and the measurement of gas velocities.

2. TRANSDUCERS

Figures 1 and 2 locate the transducers placed by CREA. Other pressure transducers and flame detectors are placed within the structure by others. The transducers placed by CREA were intended to look at two different aspects of the response, the local responses (Figure 2) and the global responses (Figure 1). The internal transducers were placed to look at the progress of the internal shock waves with respect to the recorded pressure time-histories. The main set of transducers here is those placed along the length of the rig at the 4m level. Other transducers were placed around one of the frames to look at orthogonal waves.

The global responses were measured using:

- Displacement transducers placed behind the full north wall
- Accelerometers, placed to measure the horizontal responses of the structure roof.

An instrumented cylinder was placed across the vent to indirectly measure dynamic pressures and vented gas velocities.

Table 1 lists the locations of the sensors placed on behalf of CREA. The co-ordinate origin is at the South West corner of the test rig at the top of the concrete base level with the Z xis up and the X axis along the South wall towards the East.

Table 1 Locations of Sensors

Instrument	X Co-ord (m)	Y Co-ord (m)	Z Co-ord (m)
ST-1	0.00	-0.30	0.25
ST-2	0.00	-0.65	0.25
ST-3	0.00	-0.30	0.25
ST-4	4.00	-0.65	2.00
ST-5	4.00	-0.65	6.00
ST-6	4.00	2.00	8.65
ST-7	4.00	6.00	8.65
ST-8	4.00	10.00	8.65
ST-9	4.00	12.65	2.00
ST-10	4.00	12.65	4.00
ST-11	4.00	0.00	2.00
ST-12	4.00	2.00	4.00
ST-13	4.00	3.85	2.20
ST-14	2.80	4.00	3.90
ST-15	2.80	3.90	4.00
ST-16	2.80	4.00	4.10
ST-17	1.45	4.00	4.10
ST-18	4.00	7.85	2.20
ST-19	4.00	6.00	3.90
ST-20	4.00	10.00	3.90
ST-21	4.00	12.00	2.00

Instrument	X Co-ord (m)	Y Co-ord (m)	Z Co-ord (m)
PI-1	0.80	0.00	1.00
PI-2	12.50	0.50	0.00
PI-3	27.50	0.00	1.00
PI-4	0.50	6.00	0.00
PI-5	14.00	6.00	0.00
PI-6	27.50	6.00	0.00
PI-7	0.50	12.00	1.00
PI-8	27.50	12.00	1.00
PI-9	4.50	0.60	4.10
PI-10	0.50	0.00	5.00
PI-11	14.00	0.00	5.00
PI-12	27.50	0.00	5.00
PI-13	0.50	7.00	4.10
PI-14	18.00	8.00	4.10
PI-15	27.50	6.00	4.10
PI-16	0.50	12.00	5.00
PI-17	10.00	11.50	4.10
PI-18	18.00	11.50	4.10
PI-19	27.50	12.00	5.00
PI-20	0.80	0.80	8.00
PI-21	26.10	1.70	8.00

Instrument	X Co-ord (m)	Y Co-ord (m)	Z Co-ord (m)
ST-22	4.00	3.85	5.90
ST-23	4.00	7.85	5.90
ST-24*	4.30	3.85	4.15
ST-25*	4.30	4.15	3.85
ST-26	6.00	4.00	3.90
ST-27	10.00	4.00	3.90
ST-28	14.00	4.00	3.90
ST-29	18.00	4.00	3.90
ST-30	22.00	4.00	3.90
ST-31	25.30	4.00	4.00
ST-32	25.30	4.10	4.00
ST-33	25.30	4.00	3.90
ST-34	26.60	4.00	4.00
ST-35	8.00	-7.00	1.20
ST-36	8.00	-7.20	1.50
ST-37	20.00	-7.00	1.20
ST-38	20.00	-7.20	1.50
ST-39	28.00	-0.30	0.25
ST-40	28.00	-0.65	0.25
ST-41	28.00	-0.30	0.25
ST-42*	24.40	3.85	4.15
ST-43*	24.00	4.15	3.85
ST-44+	12.70	11.90	1.54
ST-45+	12.70	11.82	1.54
ST-46+	12.50	11.86	1.58
ST-47+	12.50	11.86	1.50
ST-48+	12.30	11.86	1.58
ST-49+	12.30	11.90	1.54
ST-50+	12.30	11.86	1.50
ST-51+	12.30	11.82	1.54
ST-52	26.70	4.00	2.10
ST-53	26.70	8.00	2.10
LD-1	4.00	-0.65	4.00
LD-2	12.00	-0.65	4.00
LD-3	16.00	-0.65	4.00
LD-4	24.00	-0.65	4.00

*sensor on bolt

+ sensor on cylinder

Instrument	X Co-ord (m)	Y Co-ord (m)	Z Co-ord (m)
PI-22	19.20	8.70	8.00
PI-23	1.10	11.10	8.00
PI-24	12.80	11.20	8.00
PI-25	26.10	11.30	8.00
PI-26	4.00	0.00	2.20
PI-27	3.90	1.80	4.10
PI-28	1.10	4.00	4.10
PI-29	6.20	4.00	3.80
PI-30	4.00	9.80	3.80
PI-31	4.00	12.00	2.20
PI-32	4.00	5.80	3.80
PI-33	10.20	4.00	3.80
PI-34	14.20	4.00	3.80
PI-35	18.20	4.00	3.80
PI-36	22.20	4.00	3.80
PI-37	26.90	4.00	4.10
PE-1	40.00	6.00	1.00
PE-2	76.00	6.00	1.00
PE-3	14.00	18.00	0.00
PE-4	14.00	24.00	1.00
PE-5	14.00	36.00	1.00
AC-39	0.0	-0.3	8.3
AC-40	0.0	-0.3	8.3
AC-41	28.0	-0.3	8.3
AC-42	28.0	-0.3	8.3
AC-43	4.0	-2.8	4.0
AC-44	12.0	-2.8	4.0
AC-45	16.0	-2.8	4.0
AC-46	24.0	-2.8	4.0
AC-47	28.0	12.3	8.3
AC-48	0.0	12.3	8.3
AC-49+	12.0	11.9	1.6

3. DISCUSSION

3.1. NOISE

The results from the various tests presented in the appendices demonstrate that the noise on the recorded time-histories is a response to the structure responding to the explosion. The structure moves in two ways as the explosion develops, it displaces globally in the normally expected sway modes. However, more importantly in terms of measuring the explosion overpressure, the structure responds to the shock loading of the explosion impinging on the steel. The shock waves travel through the structure at great speed, causing the steel to vibrate at high frequencies. The pressure transducers respond to this vibration by recording the overpressure due to movement in the gas/air; the internal components of the pressure transducer have an inertial response, which results in a noise; or a combination of both. Since the additional overpressure is a consequence of the structure moving, it is legitimate to remove it from the recordings.

The actual removal of the noise can be carried out in one of two ways, either by frequency filtering or time smoothing. Given that the typical positive phase duration is of the order of 0.25 to 0.35 seconds, this implies a frequency range of between 1.4Hz and 2.0Hz. Frequency domain filtering should therefore be limited to 5Hz+. From the modal testing carried out on the frame, the first natural frequency is 6.47Hz, well above the underlying driving frequency of the explosion. Thus, frequency filtering of the pressure time-history above 5Hz would be justified.

In studying the early noise on the explosion recordings and examining the strain gauge results, time smoothing of the records, using a Welch window gives excellent cleaning of the results. Typical cleaned time-histories, using time-domain cleaning and a Welch window are presented in Figures 3 to 8.

3.2. STRUCTURAL RESPONSE

3.2.1. Dynamic pressures and vented gas velocities

The horizontal cylinder across one bay of the vent was instrumented with four pairs of strain gauges, three at the ends and one pair at the centre of the cylinder. An accelerometer (AC49) was attached at the centre of cylinder on the partially protected North 'face' to measure the cylinder response in the horizontal plane in and out of the test rig.

The cylinder was isolated from high frequency components of loading transmitted through the supports as evidenced by the smooth nature of the strain gauge measurements at the centre of the cylinder. The acceleration traces did however, show the high frequency components, which may be due to the support accelerations. The results indicate that the high frequency components are transmitted through the structure and are not local loading effects.

A method of calculating the dynamic pressure force on the cylinder is described in Section 4 of Appendix B. For test 5 the total force peaks at about 7800N with a negative phase of -2340N. Knowledge of the flame front position is necessary for the determination of gas velocities and densities. Assuming that the unburnt fuel air mixture is being expelled before the peak load is reached indicates the peak vented gas velocity was about 150 m/s. The cylinder was found to have a high damping which may be a result of the cylinder interacting with the high gas flow velocities.

Estimates have been made of the peak venting velocity but confirmation will depend on information being supplied relating to flame arrival time.

3.2.2. Global Response

The test rig was instrumented with displacement transducers, accelerometers and strain gauges to determine global structural response. Useful results were obtained this time from the displacement transducers as they were shielded from direct loading and their supports were instrumented with accelerometers.

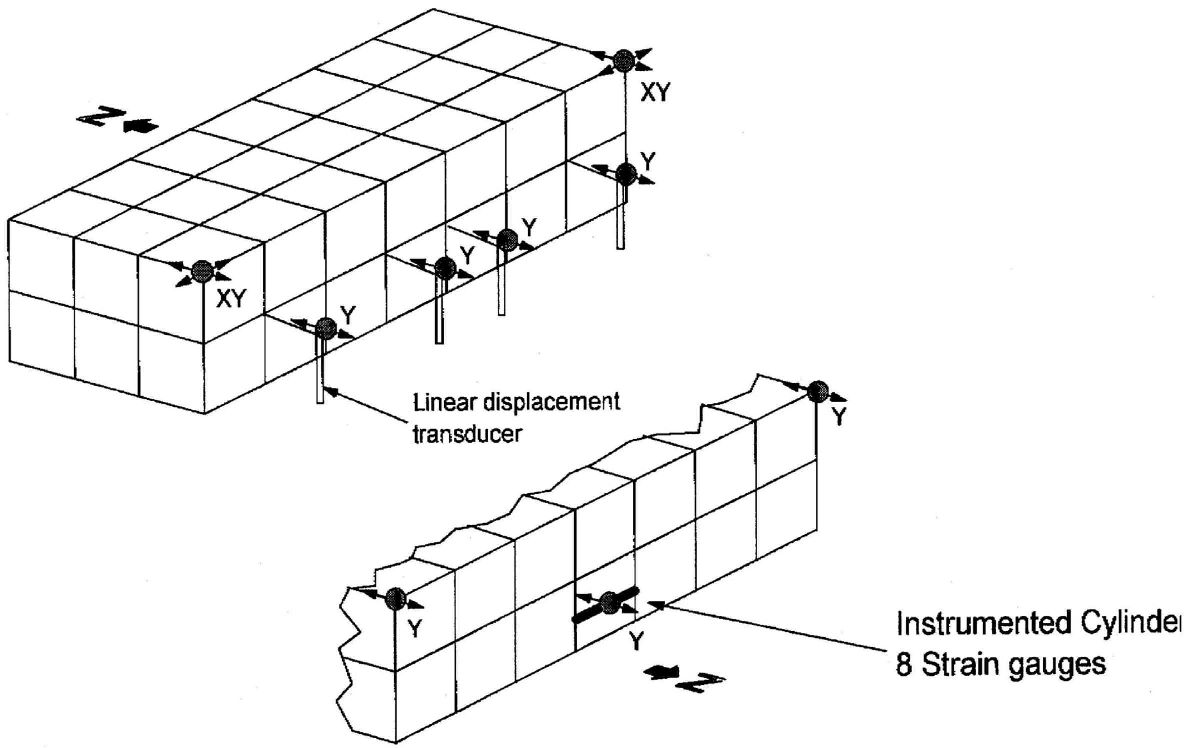
The strain gauges have been shown to provide useful results with the correct filtering out of the high frequencies. Strain gauge results have been shown to be compatible with the accelerometer and displacement transducer measurements.

The natural period of the rig in sway North/South was found to be 180 to 195 milliseconds with a damping of 3% of critical. This high level of damping may be due to the bolted method of construction for the rig. The high level of energy absorption may be a result of high frequency local responses characteristic of this type of structure.

The response of the rig has been shown to be fully dynamic as the North side of the rig responds an order of magnitude more than the South. The full loading pattern will need to be known before a response simulation of the rig can be performed, i.e. all the pressure traces should be made available. A full explanation of all the results will require a finite element model of the rig to be generated and the loading applied to the model. This was not part of the final scope for the project.

3.3. GENERAL COMMENT

This work has been carried out using data recorded by the same data collection equipment and techniques as was used for the JIP. Information that would have strengthened the conclusions of this work was either not available, due to the recording method, or was not made available. However, it is considered that the evidence collected and analysed is strong enough for full confidence to be placed in the filtering and cleaning. Flame arrival times and details of the extent of the initial gas cloud and the ignition point would have been useful for the interpretation.



Accelerometer & Displacement Positions

Figure 1: Locations of Accelerometers and displacement Transducers

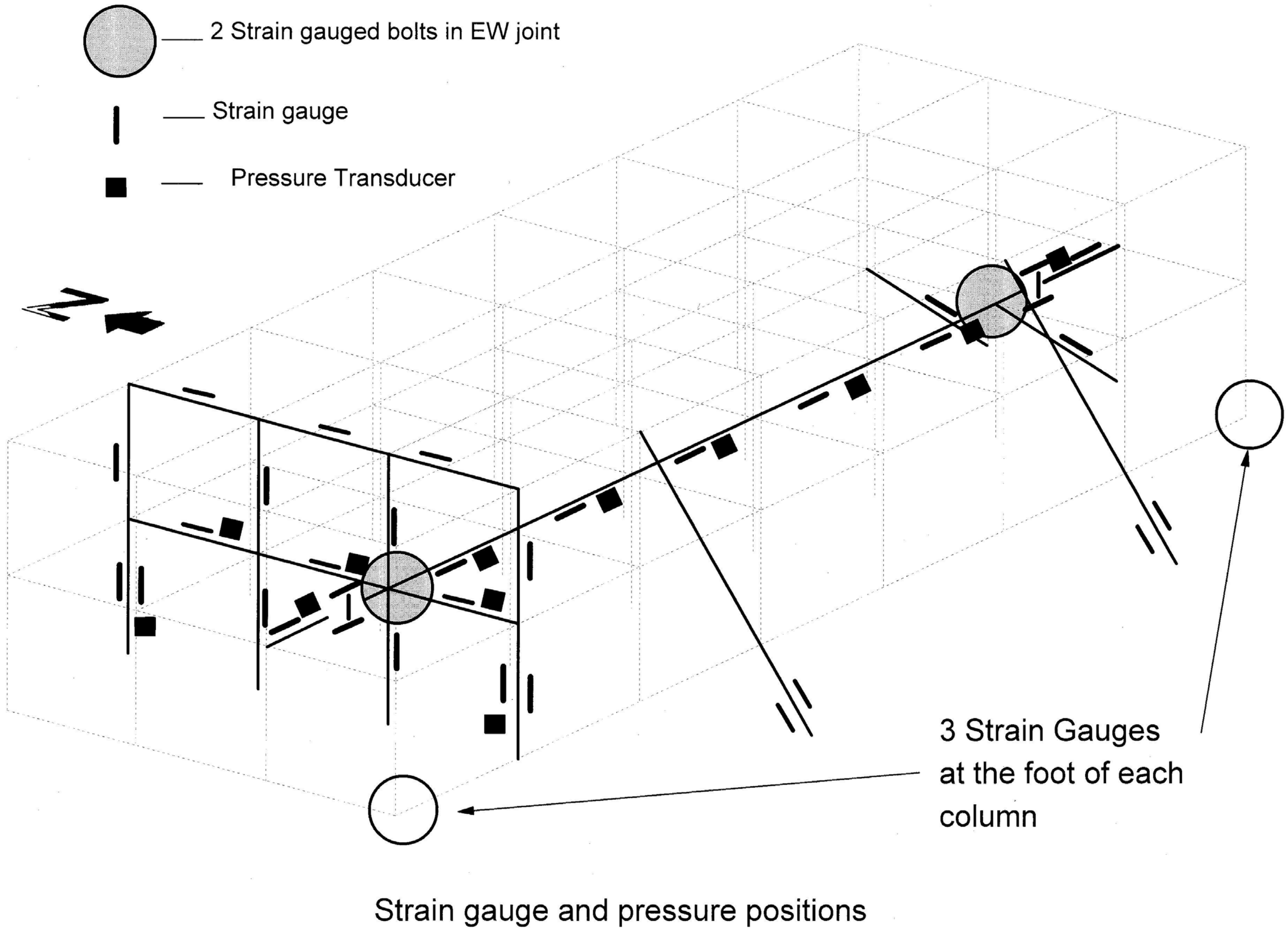


Figure 2: Locations of Strain Gauges and Pressure Transducers

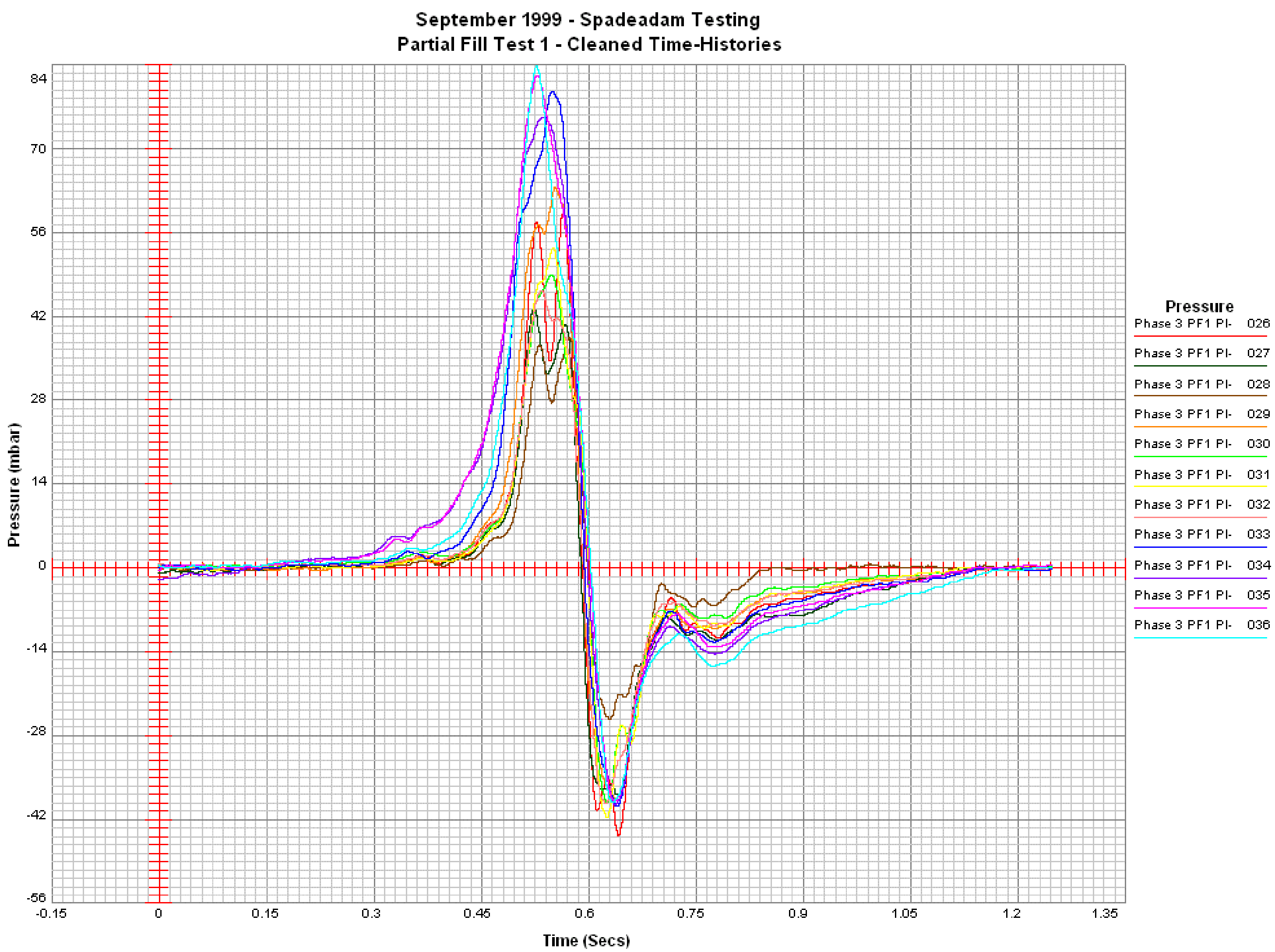


Figure 3: Test 1 Cleaned Overpressure Time-Histories

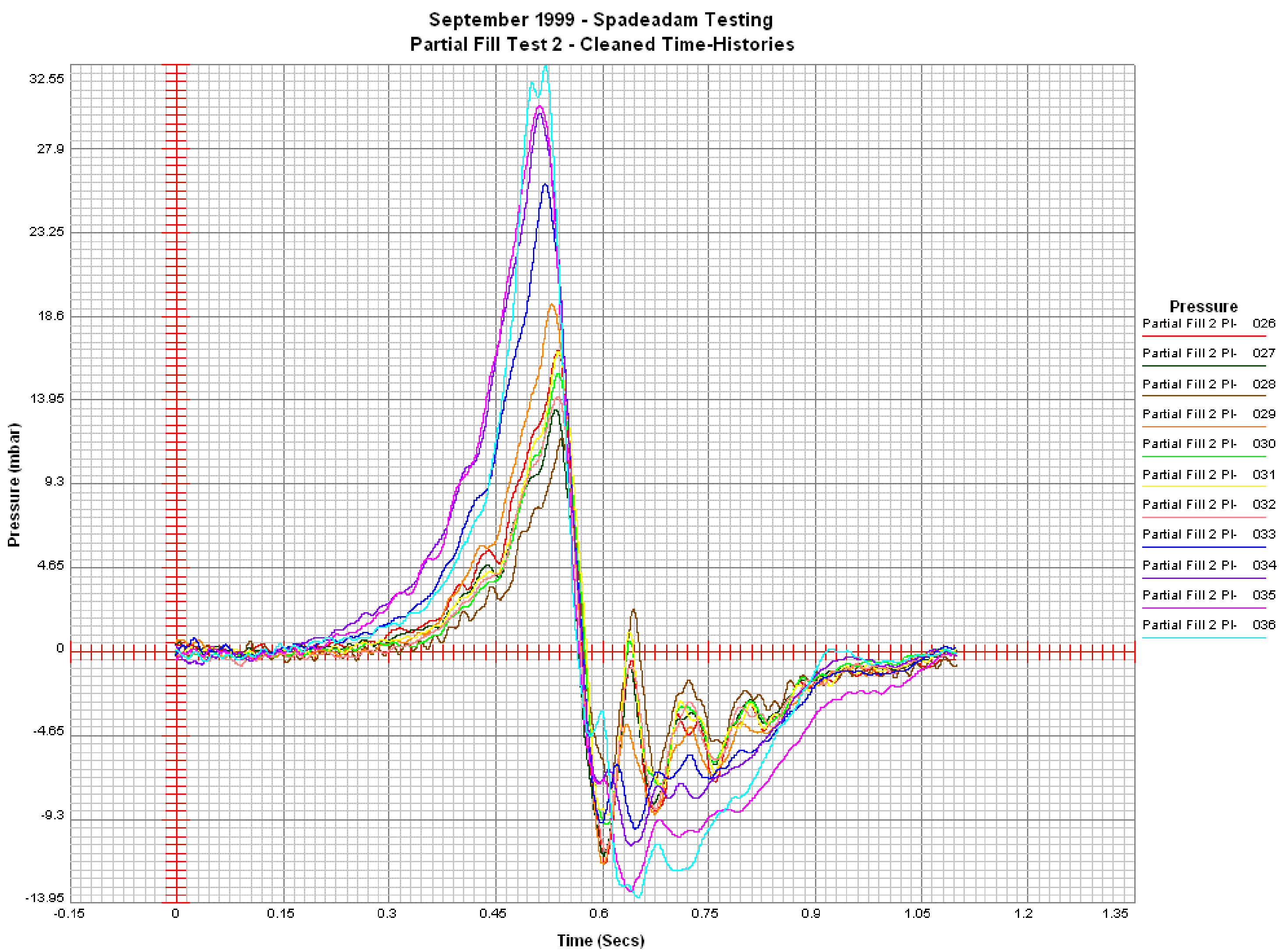


Figure 4: Test 2 Cleaned Overpressure Time-Histories

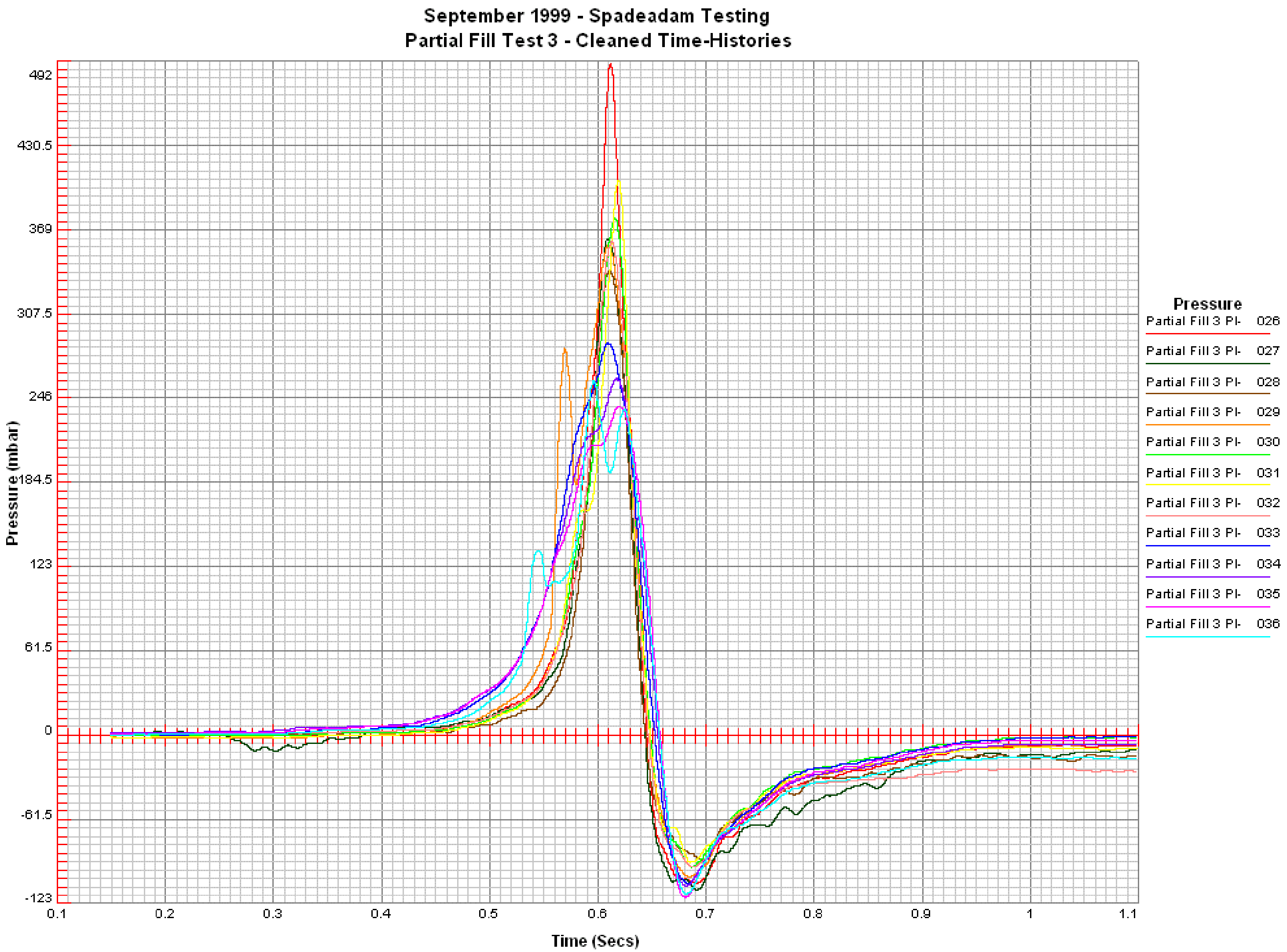


Figure 5: Test 3 Cleaned Overpressure Time-Histories

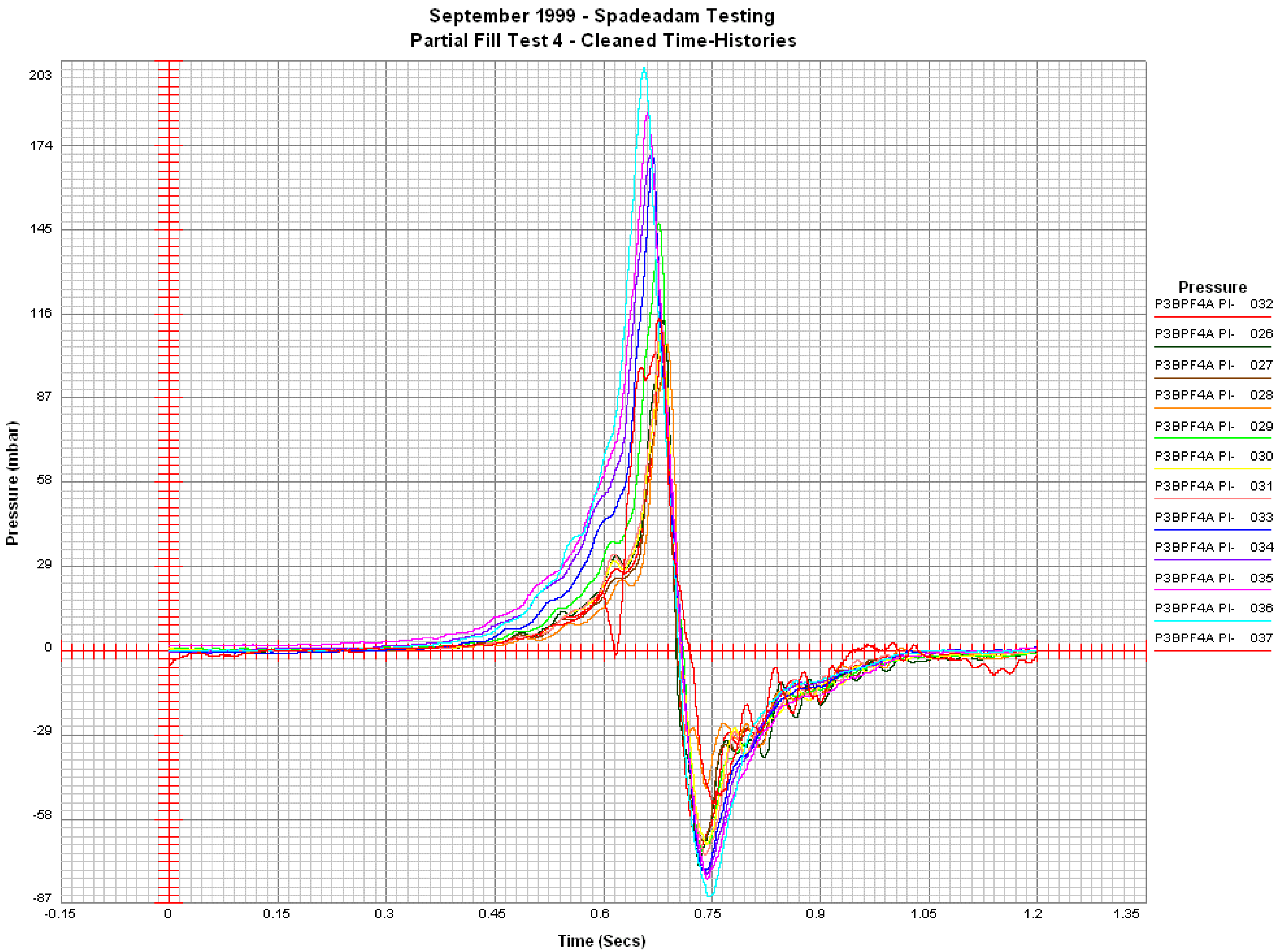


Figure 6: Test 4 Cleaned Overpressure Time-Histories

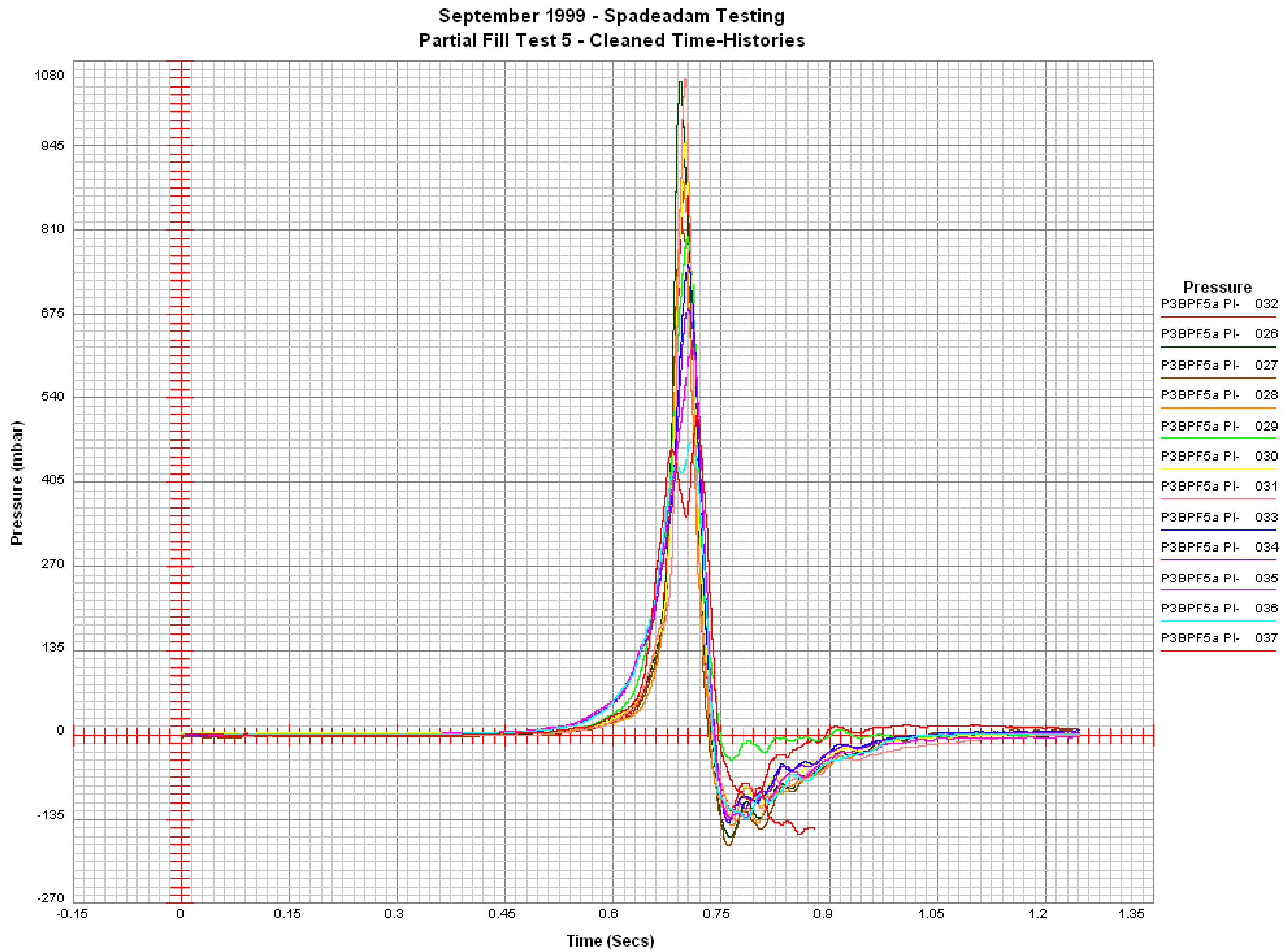


Figure 7: Test 5 Cleaned Overpressure Time-Histories

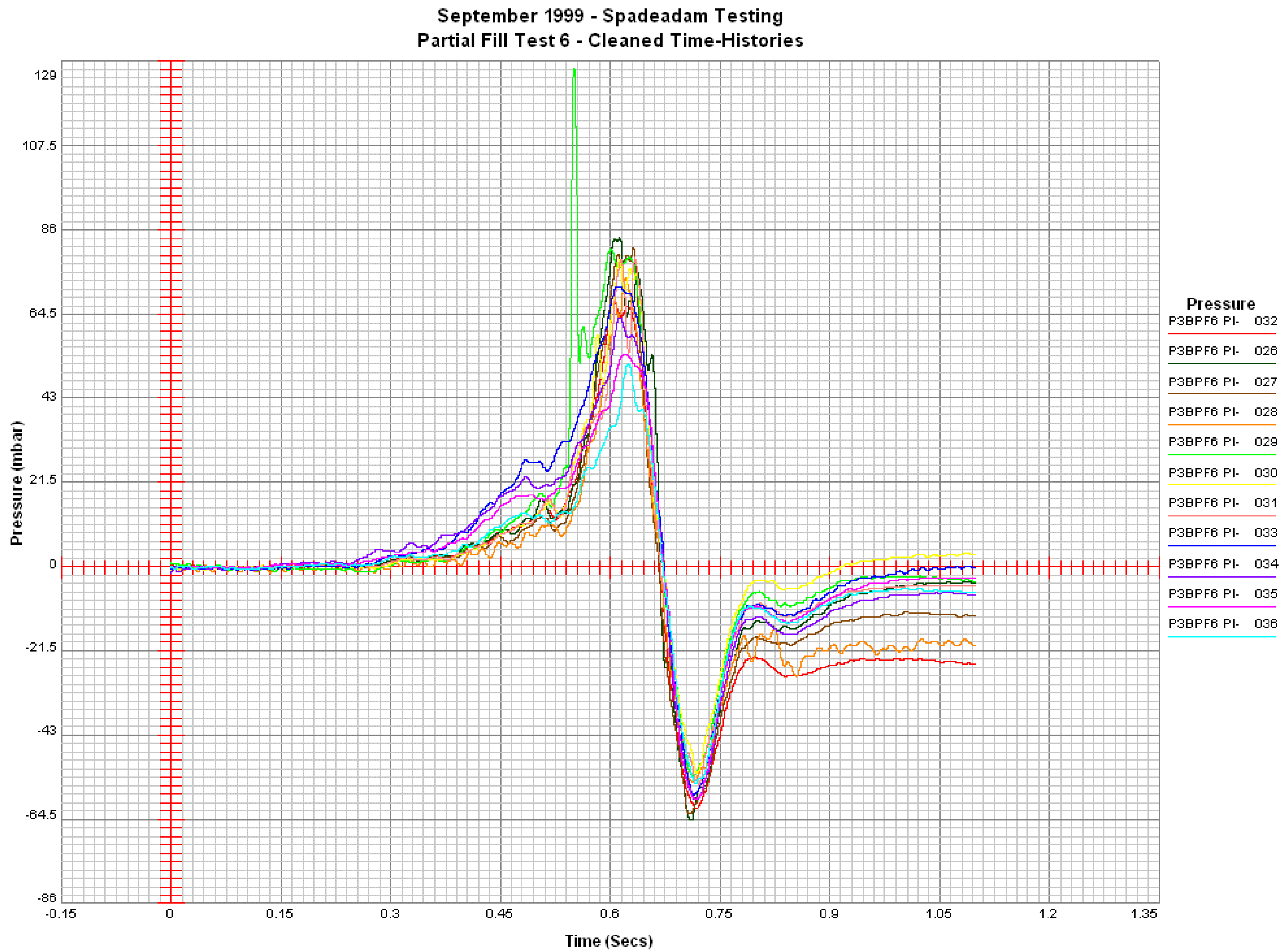


Figure 8: Test 6 Cleaned Overpressure Time-Histories