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Testing and analysis of relief device opening times

Prepared by
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for the Health and Safety Executive

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Testing and analysis of relief device opening times

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1 ABSTRACT

PSI and Sheffield University previously undertook a combined programme of physical testing and detailed analysis on a shock-tube system. The aim was to determine the opening times of several relief devices that may be used to provide protection on industrial heat exchangers in the event of a tube rupture on the high-pressure side.

The study was successful in confirming that fast-acting protection devices are available. However, the findings appeared to contradict IP Guidelines on relief valves and burst discs. In particular we expressed concerns about the applicability of the findings, in particular whether tests that had targeted the tube-rupture issue could be applied more widely.

This study shows that our concerns were well founded. There is no single opening time for devices; instead their response is primarily dependent on the level of overpressure and, in part, on their size. This means that the previous findings (i.e. a burst-disc rupture time of 1.9 msec and an opening time of 2.5-4 msec for SRVs) are not typical of industrial applications and must not be applied widely across the industry. The very fast response times are only applicable to high overpressure conditions, such as caused by tube-rupture in a heat exchanger.

In a more normal industrial context (i.e. at an overpressure of 10%) the study shows that a rupture time of about 10 msec is more suitable for graphite burst discs and about 50-100 msec for SRVs. Our results are inline with existing data (from manufacturers and research papers) although it must be noted these sources provided little information. For example, we contacted 20 SRV manufacturers for data; of these, only 8 replied and only 3 were useful.

Overall, the test conditions for the tube-rupture case are very different from those needed for normal industrial application; the constraints of the existing test facility therefore made it difficult to test industrial size devices at their full flow capacity but at only 10% overpressure. In addition, this study has been unable to determine a reliable rupture-time for steel discs because the amount of deformation that occurs before a metal disc ruptures is significant in the scale of the test-facility. It should also be noted that these results are based on a small sample with an error in consistency of up to 18%.

This means that an element of caution must be applied when discussing the findings. In, particular this applies to the SRV testing because the low-pressure tests (the most inaccurate ones) are similar to the pressure conditions that can be experienced in industry. For these reasons, and because of the paucity of accurate information from manufacturers, we believe that there is still a need for further testing, particularly aiming at the industrial usage of relief devices.

2 STUDY METHODOLOGY

2.1 BACKGROUND

The previous study into the performance of different relief devices in high-pressure applications (reported in October 2000) was successful in employing both experimental testing and detailed analysis methods. This second study therefore uses the same approach and methodology to obtain further information.

The study comprises several phases:

- A literature review and review of manufacturers' data, see Section 2.3
- A wider review of the experimental results from the previous study, see Section 2.5
- Further experimental testing using the same test-facility as the previous study, see Section 2.4
- A review of the new experimental test results (including dynamic simulation analysis), see Section 2.6.

2.2 DEVICES TESTED

As in the previous study, two different types of device were tested (namely pressure-relief valves and burst discs). These were further sub-divided so that two of each type was studied.

Table 1 Devices Tested

Device	**Type**
Spring-Loaded, Pressure-Relief Valve	Safety Valve (SRV)
	Relief Valve (RV)
Burst Disc	Reverse-buckling stainless steel
	Reverse-buckling graphite

In line with API RP 520 and industry convention, the pressure-relief valves are defined as follows:

- A safety valve is a spring-loaded pressure relief valve, actuated by the static pressure upstream of the valve and characterised by rapid opening or pop action

- A relief valve is a spring-loaded pressure relief valve, actuated by the static pressure upstream of the valve. The valve opens normally in proportion to the pressure increase over the opening pressure

Pop-action safety valves are typically described as safety-relief valves in manufacturers' catalogues and hence are known as SRVs.

2.3 REVIEW OF LITERATURE AND MANUFACTURERS' DATA

The review (undertaken by Sheffield University) comprised a standard research review of science and engineering publication databases. In addition, 20 manufacturers of relief valves and 9 manufacturers of burst discs were approached to obtain both qualitative and quantitative information.

The findings are discussed in Section 3.

2.4 EXPERIMENTAL TESTING

The overall aim of the experimental testing programme (in both the previous and the current studies) was to subject a relief device to a transient pressure rise and to measure the effect on the pressure. From this, the performance of the relief device and the opening time could be established.

Each device was therefore tested in a shock tube (see Figure 1) under three different pressure conditions. The shock-tube comprised a water-filled column, with the relief device located at the downstream end. Transient pressures were then developed by the sudden transmission of high pressure at the upstream end (i.e. from the gas reservoir into the tube).

The test-data mainly comprises the pressure measurements taken at the four Kistler pressure transducers, sited along the length of the shock-tube. But in addition, some of the burst disc tests were filmed at high speed in the previous study; and so two of these film clips have also been assessed in the wider review, one for a graphite disc and one for a steel disc.

Full details on the experimental procedures and methods are given in Section 5.

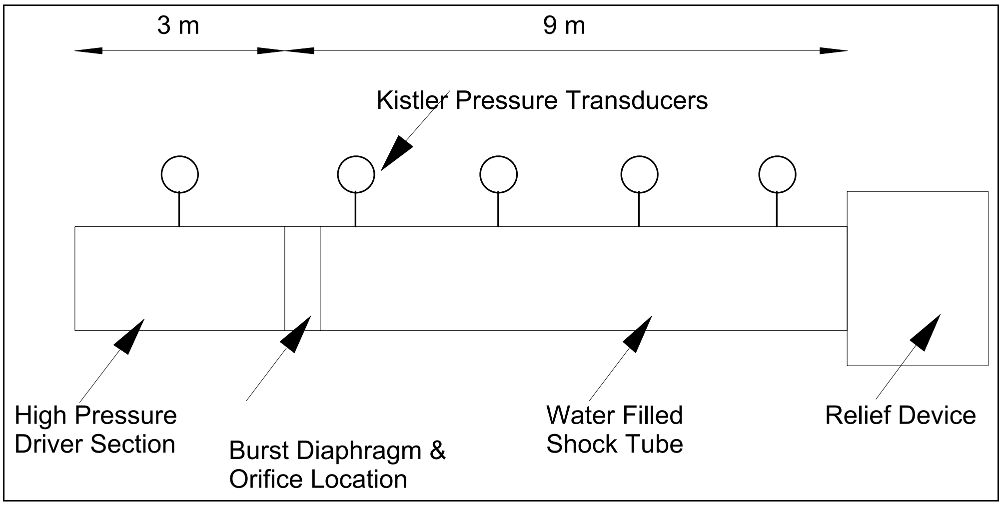

Figure 1 Schematic of Shock-Tube Used for Experiments

2.5 WIDER REVIEW OF PREVIOUS EXPERIMENTAL TEST DATA

In total, 24 shock-tube tests were undertaken in the previous study but, of these, only 10 were subjected to detailed analysis. The wider review, undertaken in this study, therefore covers the 14 remaining tests, indicated in bold on Table 2. The findings are discussed in Sections 7-9.

Table 2 Test File Matrix - Previous Study

	Relief Size (ins)	**4mm orifice**	**8mm orifice**	**15mm orifice**
Open Tube	4	Test no. 39	**Test no. 38**	Test no. 37
Burst Disc (Graphite)	4	Test no. 51	**Test no. 50**	Test no. 49
Burst Disc (Graphite)	6	**Test no. 55**	**Test no. 54**	**Test no. 53**
Burst Disc (Stainless Steel)	4	Test no. 41	**Test no. 42**	Test no. 40
Burst Disc (Stainless Steel)	8	**Test no. 48**	**Test no. 47**	Test no. 46
SRV - Spring Loaded	2 H 3 (see Note 1)	Test no. 59	**Test no. 58**	Test no. 57
SRV - Pilot Operated	2 H 3	Test no. 66	**Test no. 65**	Test no. 64
SRV - Bellows	2 H 3	**Test no. 62**	**Test no. 61**	**Test no. 60**

Note 1: The sizing of the SRV uses the industry standard where 2 = inlet diameter (ins), H = standard character defining orifice size, 3 = outlet diameter (ins)
Note 2: Relief device dimensions are given in inches to be consistent with manufacturers' specifications for the devices.

2.6 DETAILED ANALYSIS (PREVIOUS AND CURRENT STUDY)

Fundamentally, the detailed analysis comprised a dynamic simulation study using a mathematical model. We configured a hydraulic model of the shock-tube with all of the project data (i.e. tube length, diameter, driver pressure, orifice diameter etc.) to produce an accurate mathematical representation of the system. The model was then calibrated to provide good correlation between the measured and predicted results.[1] Finally, we incorporated our existing models of the burst disc and relief valves to reproduce the tests, primarily using trend studies[2] to determine the opening times of the devices.

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[1] Some parameters, such as the internal hydraulic roughness of the tube and the amount of free air in the test-water are not unique data items and can vary between systems. These are therefore adjusted in the calibration

[2] A trend study is one in which one variable is systematically varied, whilst all other parameters remain unchanged. These studies are frequently used to size/specify equipment and to replicate different pressure/flow conditions in pipelines and piping systems

In addition to the dynamic simulation, we also undertook wide-ranging appraisals. We have extensive experience in the effects of surge pressure changes in pipes and piping systems and this understanding was applied to the evaluation of the physical test results themselves, as well as the findings from the dynamic simulation.

For example, one of the benefits of dynamic simulation is the ability to provide additional information on the behaviour of a piping system, to supplement the data from SCADA systems, transducers and pressure gauges.[3] This information, equivalent to the output from virtual instruments, provides further diagnostic information; and this, together with our experience, means that our evaluation of the test results was particularly useful.

The benefits of this approach were evident during the initial testing phase of the previous study. We were able to interpret the test results and suggest that the presence of air in the shock-tube was generating 'non-standard' behaviour. Sheffield University then identified the source of the problem and eliminated it with revised test procedures. Subsequently, we obtained very good correlation between the measured and simulated results for the Open Tube tests and were therefore confident that the dynamic simulation phase with the relief devices would provide a meaningful outcome.

The findings are discussed in Sections 7-9.

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[3] This is widely used in industrial applications and is extremely helpful in troubleshooting; it is a non-invasive and low-cost way of investigating operating problems

3 LITERATURE REVIEW

3.1 INTRODUCTION

The main purpose of study as a whole is to resolve the anomalies from the previous phase of the study (Ref. 1); these stemmed from our comparison between the opening times predicted in the study and those contained in the IP-HSE reports (e.g. Ref. 6). The particular objective of the literature review, undertaken at Sheffield University, was therefore to trace and support the documented opening times in the IP-HSE report.

The review comprised two activities, namely a search of science/engineering publication databases and an approach to the main manufacturers of relief valves and burst discs.

3.2 MANUFACTURER RESPONSE

The list of manufacturers who were contacted for information is given on Table 3 and the statistics for their response are shown on Table 4. The response from the disc manufacturers was higher and more were useful.

Table 3 Data Review - Manufacturer List

Relief Valve Manufacturers	Rupture Disc Manufacturers
Anderson Greenwood	Oseco
Fisher	Pressure Systems
Oseco	Advanced Rupture Disk
Pressure Systems	Rembe
Braunschweiger Flammenfilter	Fike
Kunkle	Newson Gale
Safety Systems Technology	Elfab
Southwestern Controls	Rom Sur
Consolidated	Continental Disc Corporation
Taylor Valve Technology	
Rockwood Swendeman	
Spencer	
Farris	
Societe GMI	
Broady	
Nabic	
Conbraco	
Lonergan	
Vilter	
RegO Products	

Table 4 Data Review - Manufacturer Response

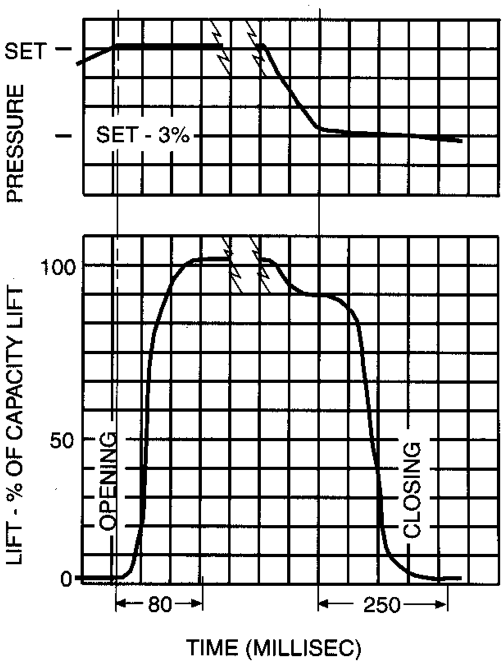
Type	Number Contacted	Number Replied	Number of Useful Replies	% Useful Replies
Relief Valve	20	8	3	15.0
Rupture Disc	9	4	4	44.4

3.3 MANUFACTURER DATA - SAFETY AND RELIEF VALVES

The majority of manufacturers did not have information about the opening times of their safety and relief valves. The main reason for this would appear to be that the manufacturers believe that the expected rates of pressure rise (i.e. in the systems which are being protected) are slow compared to the expected response time of the valves.

Of those manufacturers who were able to provide some information, there was a general similarity among the data. This is summarised as follows:

- Farris have indicated that 50% of the valve lift will occur in 50 msec, with the remaining 50% occurring on a time-scale that depends on the rate of pressure rise.
- Figure 2 overleaf shows data from the Crosby Isoflex valve. The upper trace shows a relatively slow rate of pressure rise toward the valve set pressure - at approximately 20% of the set pressure per second. The lower trace shows full lift within around 80 msec, which is of the same order of magnitude of the Farris valve.
- Most manufacturers were only able to say that the opening time would increase with the size of valve
- Some respondents (e.g. Tyco) indicated the difficulties of generalising with different types of fluids, temperatures etc.



Typical Valve Opening and Closing Curve.

Figure 2 Manufacturer Data - Crosby Isoflex Valve Data

3.4 RESEARCH DATA - RELIEF VALVES

Much of the research work undertaken by independent sources (i.e. universities etc) presents detailed analysis of the theory of valve operation but little is validated against test data.

- Parry (2) makes reference to typical relief valve opening times of 'tenths of a second', although the justification of this figure is not given through cited references.
- Dynamic analysis carried out on a pop-action relief valve by Watton and Xue (3) generated measured data on the pressure-flow characteristics, effective mass of the spindle components and damping constant. Dynamic studies on this valve showed typical response times of 50 msec for small imposed flowrate changes.
- Francis and Betts (4) have carried out compressible flow studies through a pop-action relief valve (FIG 500 with bore diameter of 40 mm) and quote a transient opening time of around 50 msec for their valve.
- These values are comparable to those quoted by Thornton (5) for a spring-loaded valve where time to fully open is between 80 - 120 msec.
- Values are also quoted in (6) for typical values for a pilot operated valve, being 80 - 350 msec. This type of valve however, has not been considered for the transient overpressure

situation of current interest since the biasing back-pressure is undeveloped for the transient case.

- A tested value of 25msec can be estimated from the work of Kruisbrink (9) for a 3K4 safety valve in liquid service but it is difficult to determine whether or not this is in a high-overpressure condition
- All of the other papers were concerned with pressures that were in the normal operational range for the relief device.

3.5 MANUFACTURER DATA - BURST DISCS

A few manufacturers were able to provide some information on their burst disc behaviour in the context of industrial applications (i.e. again applying to quasi-static conditions with slow rates of pressure rise).

- Oseco have quoted a typical opening time across their range of 0.5 msec.
- Rembe cannot provide measured values but expect times to be within 1 msec.
- Continental provided more definite information indicating that for forward acting discs (concave side to the high pressure), opening times are 6 - 9 msec. For reverse acting discs values are typically 1 - 3 msec.
- Fike, who also produce bursting panels for explosion protection, indicate that the general rule that they apply is an opening time of 1 msec per 25 mm of relief diameter.

3.6 RESEARCH DATA - BURST DISCS

The work from independent sources can be summarised as follows:

- Among the earliest use of relief device timing information is the work of Simpson (7), who was concerned with the high-pressure tube failure scenario. The analysis work carried out used burst disc times of 0.5 msec and these were taken from the measured times associated with shock-tube diaphragm rupture.
- More recent modelling work (8) on the tube rupture problem using a burst disc has taken an assumed value of 5 msec to the fully open condition.
- Dynamic modelling work referred to in (6) has also used disc opening times in their analysis and results have been found to be more consistent with overall experiments when values in the range 0.1 - 10 msec have been used.

3.7 CONCLUSIONS

This review shows that relief valves appear to have opening times in the range of 50 - 100 msec, under the conditions of small pressure deviations above the set pressure. This is consistent with the little available information from manufacturers and measured literature values.

Manufacturer's data on burst disc times is also rather limited although those which are able to provide information are more confident in the values claimed. Thus, values are quoted to be in the range of 1 - 10 msec, for discs up to 250 mm in diameter.

Overall we note that the literature values which have been used in analytical work are poorly referenced although they are typically in the range quoted by the present manufacturers.

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4 EXPERIMENTAL STUDY: PRE-TEST REVIEW

4.1 INTRODUCTION

One of the basic aims of this study was to align the findings to industry. A concern from the earlier study was that the 2in SRV was not representative of industrial usage and that the fast opening could be a function of its size. Additionally, there was a big disparity between the capacity of the burst discs and the SRV (i.e. the discs were over-sized and the SRV was under-sized in comparison with the relief requirements of the shock-tube).

A review of the test-facility and the sizing of the devices was therefore undertaken (before the test programme began) to try and rationalise the capacity of the facility and the devices, whilst ensuring that the sizes were more typical of industrial use.

4.2 SELECTING THE DEVICE SIZING

The sizing mismatch in the previous study is exemplified by using the sizing equation from API RP 520[4]. For a nominal set pressure of 15 barg and a back-pressure of 2 barg, the capacity of the largest burst disc studied previously, was over 40 times greater than the 2in SRV (Table 5).

The sizing of the devices was therefore reviewed for this current study to achieve both better compatibility between the devices themselves and compatibility with industrial applications. Typically, 3in and 4in devices were therefore selected because we believe that these are more representative of the sizes used in industry and, as shown on Table 5, because similar capacities could be achieved for the burst discs and SRV.

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[4] API RP 520 covers the Recommended Practice for the 'Sizing, Selection and Installation of Pressure-Relieving Devices in Refineries'

Table 5 Device Capacity (after API 520)

Phase	**Device**	**Size**	**Capacity (USgpm)**
Original Study	Burst Disc (Stainless Steel)	8 in	13114
	SRV	2 H 3	324
Current Study	Burst Disc (Stainless Steel)	3 in	1786
	SRV	4 L 6	1179

Note 1: The sizing of the SRV uses the industry standard nomenclature where 2 = inlet diameter (ins), H = standard character defining orifice size, 3 = outlet diameter (ins)

Note 2: Device capacity is given in USgpm, in line with API RP 520

4.3 SELECTING THE TEST-PRESSURES

The previous study provided three groups of test-data, differing because of the size of the orifice on the driver-end of the shock-tube. For example, the largest orifice (15mm) gave a high-pressure test with peak pressures of over 60 barg at the test-end of the tube;[5] but this is over four times the nominal set pressure of the relief devices. In contrast the smallest orifice (4mm) gave a low-pressure test; the transient pressures were only a few bar above the set pressures and hence more suited to the industry criterion.[6]

For the current study, we therefore attempted to select test conditions that were similar to those that occur in the field but we found that this could not be easily achieved. For example, the low-pressure test is obviously most suitable when considering the pressure criterion but the associated flow is too low. The dynamic simulation study (which formed part of the detailed analysis) showed that the associated flow in the shock-tube was only 16% of the capacity of the SRV (Table 6). And, as shown in the previous study, this over-capacity (in flow terms) led to the well-known phenomenon of valve-chatter. Conversely, the flows were more compatible for the high-pressure test[7] but the associated pressures is not, being over four times the set pressure of the devices.

These issues are summarised on Table 6. Firstly, the table shows the target requirements i.e. the ideal pressure and flow conditions that would satisfy two of the relief devices that had been selected, the 3in burst disc and the 4L6 SRV. Secondly, for comparison, the pressure/flow conditions achieved during the high-pressure and the low-pressure test in the previous study are also included.

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[5] The pressure of 62.5 barg is taken from the Open Tube tests

[6] The sizing criterion for a relief device in API RP 520 is to provide the required capacity at a pressure of only 10% above the set pressure of the device

[7] The flow in the tube is 1162 USgpm compared with 1179 USgpm for the 4H6 SRV

Table 6 Selection Matrix for Test Conditions

	Pressure Comment	Pressure (barg)	Flow Comment	Flow (USgpm)
Target (3in burst disc)	Requirement is 110% of set pressure (15 barg)	16.5	API 520 capacity	1786
Target (4 L 6 SRV)	Requirement is 110% of set pressure (10 barg)	11.0	API 520 capacity	1179
High-Pressure Test	Measured in Open Tube Test	62.5	Calculated in Dynamic Simulation Study	1162
Low-Pressure Test	Measured in Open Tube Test	16.9	Calculated in Dynamic Simulation Study	190

Our overall conclusion was that the existing test-facility is suitable for addressing one of the objectives of the study (i.e. resolving anomalies from the previous study) but that there would be an inevitable compromise in trying to satisfy the industry objective.

We therefore elected to retain the original test conditions (of pressure and flow) for the test on the steel burst discs and on the SRVs (i.e. for the majority of the tests) as the test-matrix covered the full range of both pressure and flow criteria.

4.4 SELECTING THE TYPES OF DEVICE

For continuity, this study examined the same types of relief device that had been studied previously i.e. a spring-loaded SRV and a reverse-buckling stainless steel bursting disc. But for the graphite discs we chose a slightly different strategy. Arguably the best results from the previous study related to the graphite burst discs; the calculated opening time showed the best correlation with the measured data (see Figure 23) and was consistent with the values used in the IP study, which formed the basis of the IP Guidelines. We therefore felt that there was little benefit in selecting discs that simply replicated the previous study.

At the same time that the devices were being sized, the extended analysis of the previous tests showed the importance of the disc shape, in particular the reverse-buckling type. In the previous study, we had used flat-disc, machined-type graphite discs and so we also selected reverse-buckling graphite discs[8]for this study, i.e. the same as the steel discs. However, this posed a further problem in that these discs are only available commercially with low burst pressures (typically 1.0-3.5 barg). To comply with this, the test-pressures were therefore reduced correspondingly.

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[8] These discs were compressed graphite

5 EXPERIMENTAL STUDY: METHODOLOGY

5.1 INTRODUCTION

The experimental aims and methods were briefly introduced in Section 2.4. This section therefore provides further details on:

- The relief devices that were tested (Section 5.2)
- The experimental facilities and methods (Section 5.3 and 5.4)
- The test conditions (Section 5.5)

5.2 RELIEF DEVICES - TEST SPECIFICATION

The specification of the relief devices is listed below:

Table 7 Relief Device - Basic Data

Device	Type	Size	Orifice	Set Pressure (barg)
Safety Valve (SRV)	Pop Action	2in inlet 3 in outlet	H	15
		4in inlet 6 in outlet	L	10
Relief Valve	Proportional Lift	4 in	Standard DN 100	10
Burst Discs	Stainless Steel (Reverse buckling)	3 in	N/A	14.5
		4 in	N/A	14.6
Burst Discs	Compressed Graphite (Reverse buckling)	3 in	N/A	3.6
		4 in	N/A	1.0

5.3 EXPERIMENTAL FACILITIES

The main facility was a shock-tube of 100mm internal diameter. This consisted of a driver section (containing high-pressure air[9]) which was separated from a short buffer section (containing atmospheric air) by an aluminium burst disc. The buffer section was

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[9] Air was supplied to the driver section from a compressor via an air reservoir and a number of electrically operated isolation valves.

connected to the water-filled section of the tube via a plate, in the centre of which was the discharge orifice. To retain the water during filling, the downstream side of the orifice plate was sealed with thin aluminium foil or plastic film.

Four Kistler pressure transducers (K1 - K4) were located at positions along the water-filled section to record the transient pressure profile. K1 was also used to trigger the data acquisition because it was closest to the orifice. K4 was located as close as possible to the relief device at the opposite end of the tube to minimise the transmission delay during device opening. A separate pressure transducer, D1 was used to monitor the driver-pressure and provided the starting pressure at the point of rupture. The Kistler transducers were re-calibrated before the set of experiments. The pressure transducers had a response time of around 6 μsec and raw voltage signals were acquired to a computer acquisition card at a rate of 20kHz on each channel.

Slight variations in geometry were used for different groups of tests and these are represented in the figures below.

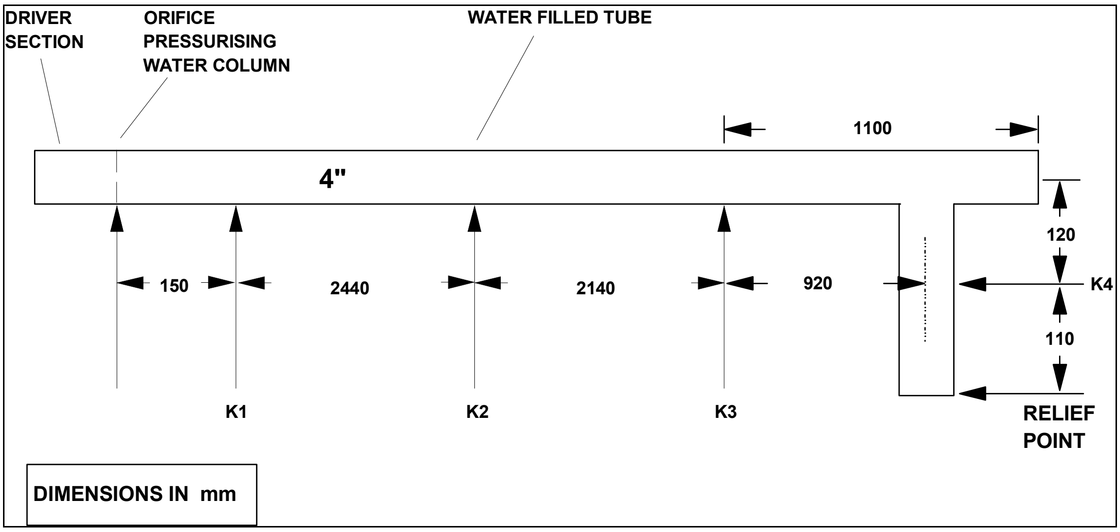

Figure 3 Shock-tube Geometry and Dimensions for Tests 1 - 3.

(K1 - K4 represent positions of Kistler pressure transducers)

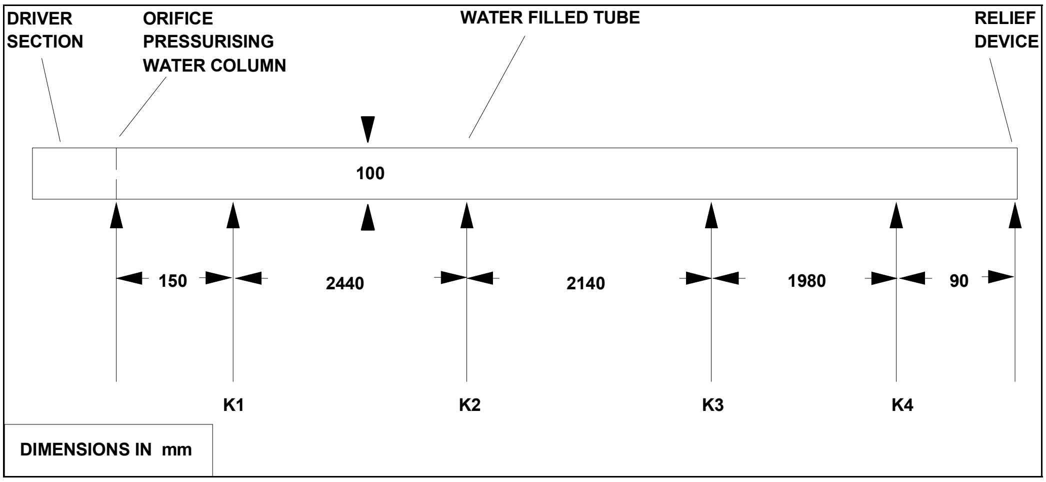

Figure 4 Shock-tube Geometry and Dimensions for Tests 4 - 9, 11 - 13 and 15-18

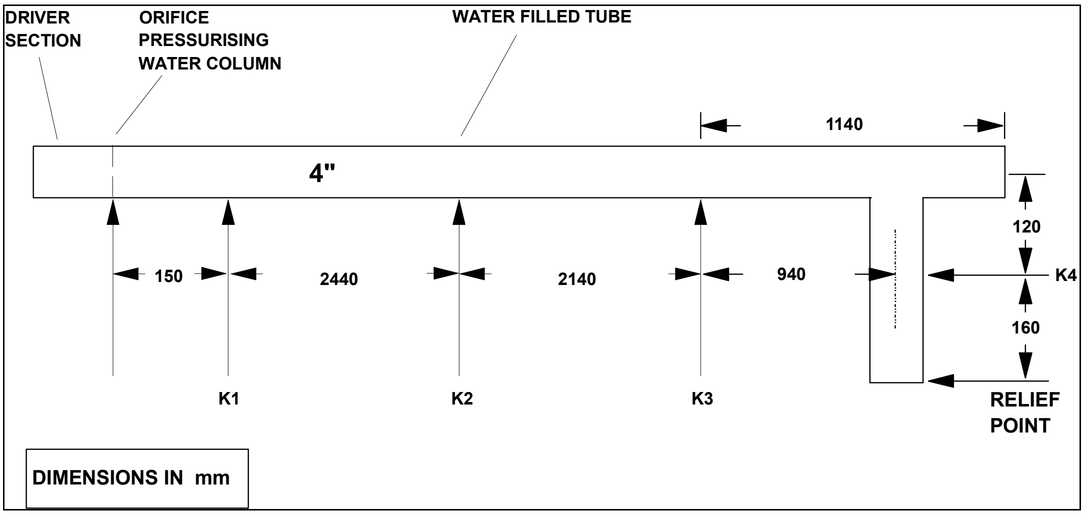

Figure 5 Shock-tube Geometry and Dimensions for Tests 19 - 21

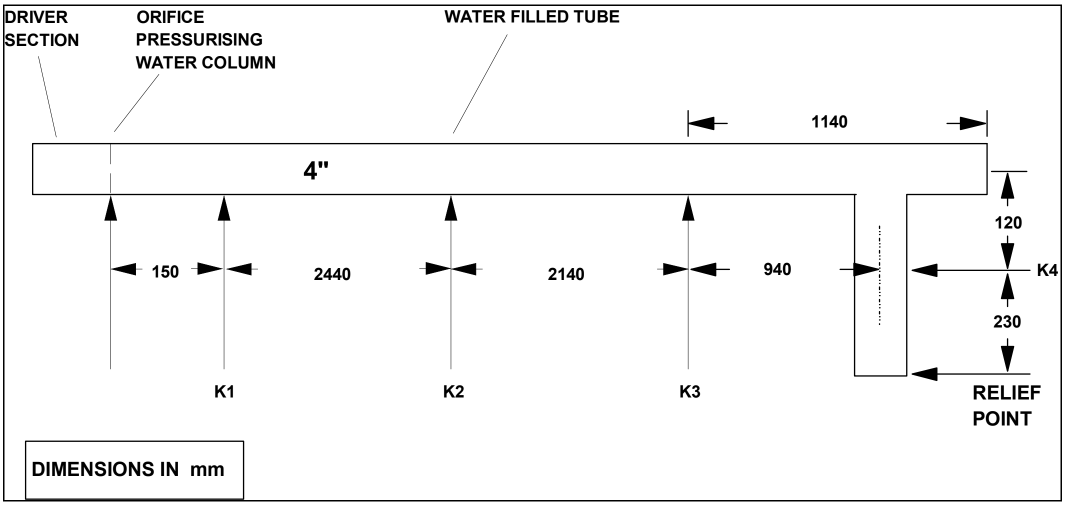

Figure 6 Shock-tube Geometry and Dimensions for Tests 23 - 25

5.4 EXPERIMENTAL METHOD

Aluminium burst diaphragms were produced in-house and could be designed to rupture at any prescribed pressure; tests were therefore conducted at pressures of 100 barg ± 10% for most devices and 20 barg ± 10% for the graphite discs.

The removal of air bubbles from the water-filled tube and connections was an important requirement to avoid air entrapment because this contaminated the pressure traces by spurious reflections from gas interfaces. Water inlets and outlets and the fabrication detail around the relief devices were all optimised such that no air pockets could remain during filling.

From the previous study it had been found that small air bubbles could remain immobile along the surface of the tube during filling. The flow velocity of water during tube filling was important for their removal and therefore water supply and outlet diameters were maximised whilst the shock-tube was also inclined at a gradient of 1:75. When the tube was full of water, surfactant was mixed with the feed water to aid bubble flow and this feed was maintained until no further bubbles were obtained in the outflow. Fresh water was finally flushed through the tube. This procedure was ultimately judged to be satisfactory although the removal of the smallest bubbles remained a central part of the experimental procedure before each test.

Each test then consisted of the slow pressurisation of the driver section until the aluminium diaphragm ruptured. Data acquisition on all Kistler channels and the driver stagnation pressure was then triggered by the voltage rise on K1. A small proportion of pre-triggering time was also collected and allowed an exact determination of the pressure at rupture.

The pressure wave then took around 5.5 msec to arrive at K4 and it was therefore considered sufficient to collect 250 msec of data. Only the early part of this is relevant to the relief device opening and is the focus of analysis within the charts.

For the relief devices, holders for both types of burst disc (stainless steel and graphite) were fabricated according to manufacturer's specification.

5.5 TEST CONDITIONS

Each of the devices was tested at three different conditions of transient pressure. The range of conditions was achieved by varying the gas pressure in the driver-section of the shock-tube and choosing the burst diaphragms appropriately. In addition, three different sizes were available for the upstream orifice, as indicated in Figure 1.

Thus:

- The driver pressure was typically 20 barg for the tests on the graphite burst discs
- The driver pressure was typically 100 barg for all other tests
- The discharge orifices were 4mm, 8mm and 15mm in diameter.

This combination provided 24 sets of results, including those with an open-ended tube (thin plastic film). These are summarised in the test matrix shown below, where test numbers refer to specific data sets generated.

Table 8 Test File Matrix - Current Study

Relief Device	Size	Driver Pressure (barg)	4mm Orifice	8mm Orifice	15mm Orifice
Safety Valve (SRV)	2 H 3	100	Test no. 2	Test no. 1	Test no. 3
	4 L 6	100	Test no. 23	Test no. 24	Test no. 25
Relief Valve	4 in	100	Test no. 21	Test no. 20	Test no. 19
Stainless Steel Disc	3 in	100	Test no. 6	Test no. 5	Test no. 4
	4 in	100	Test no. 7	Test no. 8	Test no. 9
Graphite Disc	3 in	20	Test no. 18	Test no. 16	Test no. 15
	4 in	20	Test no. 13	Test no. 12	Test no. 11

6 EXPERIMENTAL STUDY: CONSISTENCY REVIEW

6.1 INTRODUCTION

Some of the tests that were undertaken in the previous study were repeated in this current study, allowing the consistency (i.e. repeatability) and accuracy of the testing to be estimated.

6.2 SRV TESTS

The test on the 2H3 SRV were directly repeated which provided the best indication of the repeatability of the tests.

The results showed excellent comparison for the medium pressure test; as shown on Figure 7, the phasing of the pressure waves is the same and the difference in the peak pressures is less than 1.5% (59.3 barg compared against 58.6 barg). Similarly the high-pressure tests show very good comparison but with an offset in the phasing of the wave of 0.6 millisec.

The weakest comparison occurs with the low-pressure test (Figure 8). The wave shape is broadly similar and both sets of results show the valve chatter problem discussed in the original report.[10] However, the peak pressures differ by 5.6 bar, some 17.6%.

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[10] This is not however apparent on Figure 8 because the graph displays only the first 0.02 seconds of the tests.

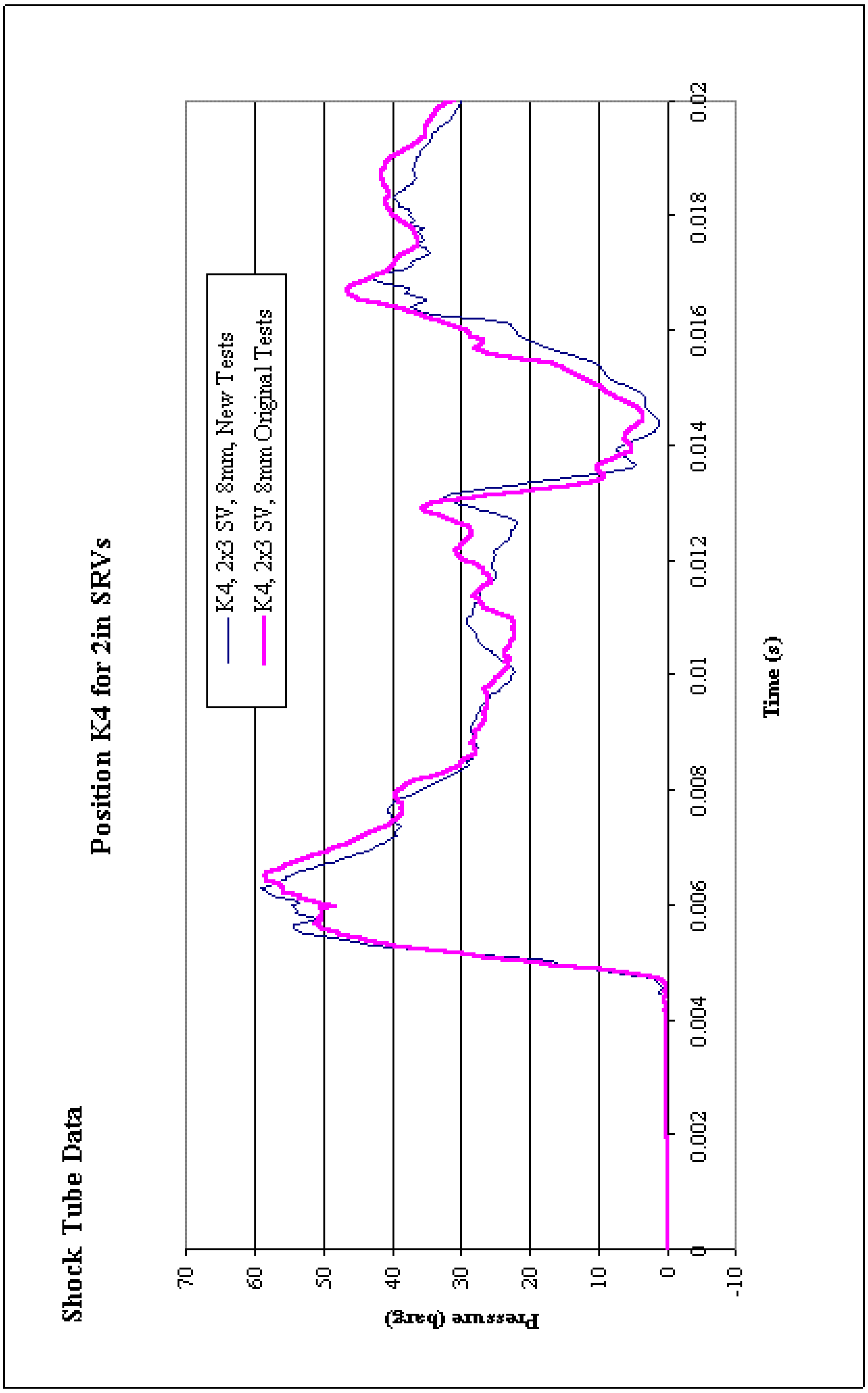

Figure 7 Measured Data - Comparing SRV Tests (Medium Pressure)

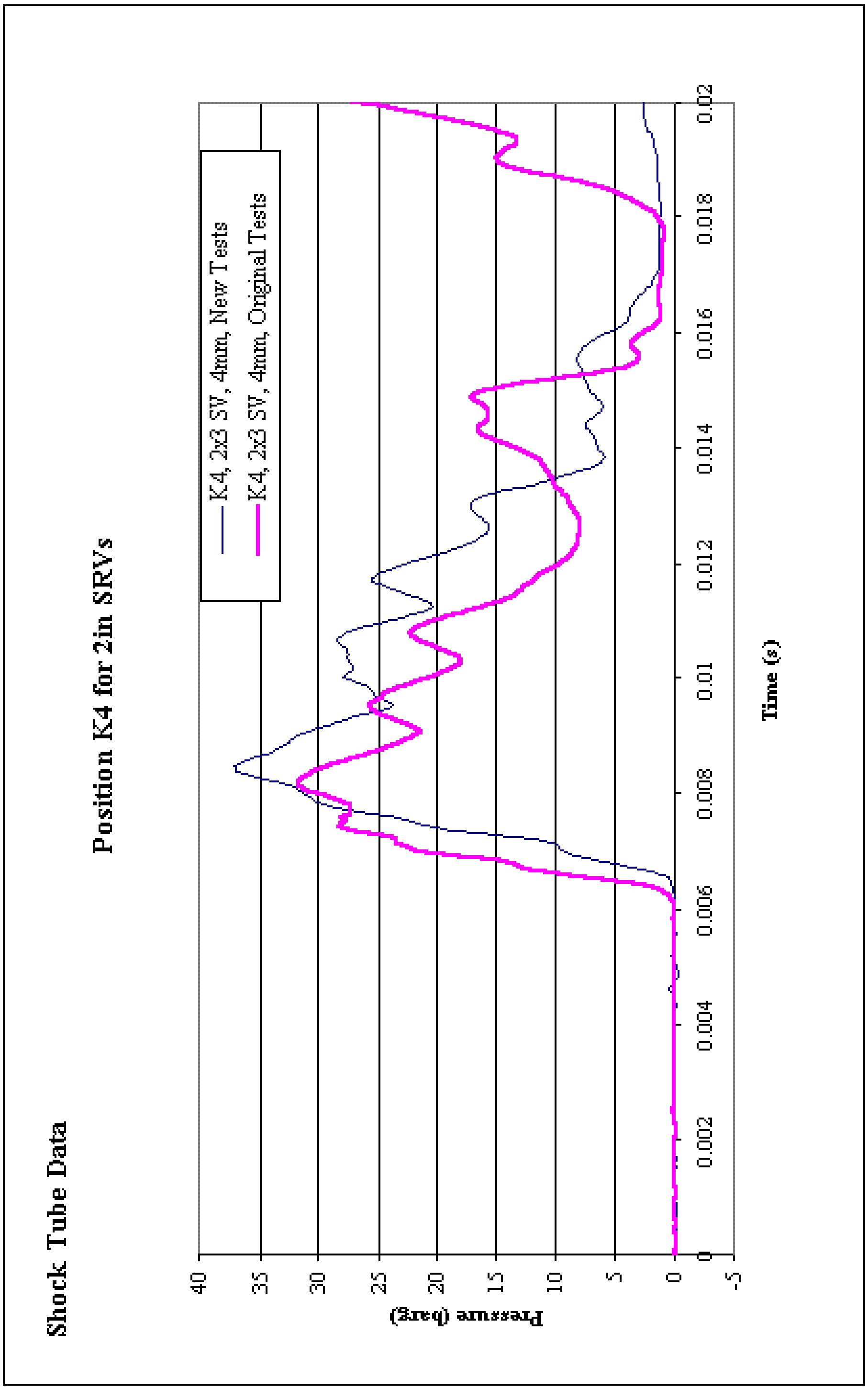

Figure 8 Measured Data - Comparing SRV Tests (Low Pressure)

6.3 BURST DISC TESTS

The repeatability trend for the steel burst discs is the opposite of the SRV trend. There is an offset in time for the low-pressure results (Figure 9) but otherwise the comparison is good with a difference in the peak pressures of only 0.2 bar (1.1%).

However, the high-pressure test gives the weakest comparison (Figure 10). The time-offset is small but the difference in the peak pressures is over 18% (7.4 bar).

6.4 CONCLUSIONS

Overall, the SRV tests show a high level of repeatability under the medium and high-pressure conditions but the weakest comparison occurs with the low-pressure test with the peak pressures differing by almost 18%. Similarly, the burst disc tests show good repeatability at two conditions (low and medium) but an error of 18% is again apparent in the worst case.

We do not have enough sets of results to undertake any statistical review; nor can we isolate the reason for these differences. We cannot determine whether there was a significant difference in the pressure/flow conditions generated in the shock-tube or whether the devices are unduly sensitive to a small variation in conditions. Overall, this means that an element of caution must be applied when discussing the findings. In, particular this applies to the SRV testing because the low-pressure tests (the most inaccurate ones) are similar to the pressure conditions that can be experienced in industry.

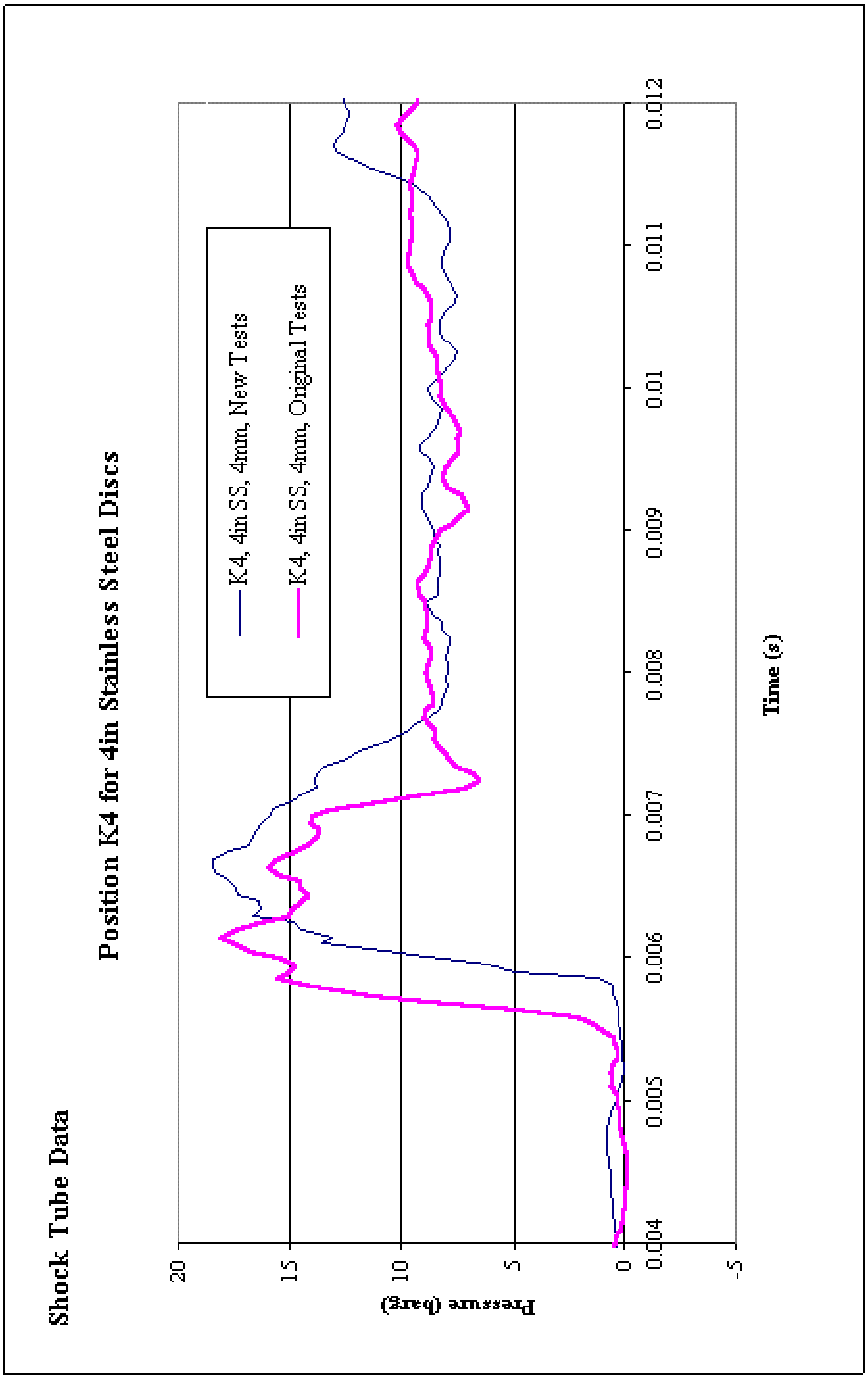

Figure 9 Measured Data - Comparing Burst Disc Tests (Low Pressure)

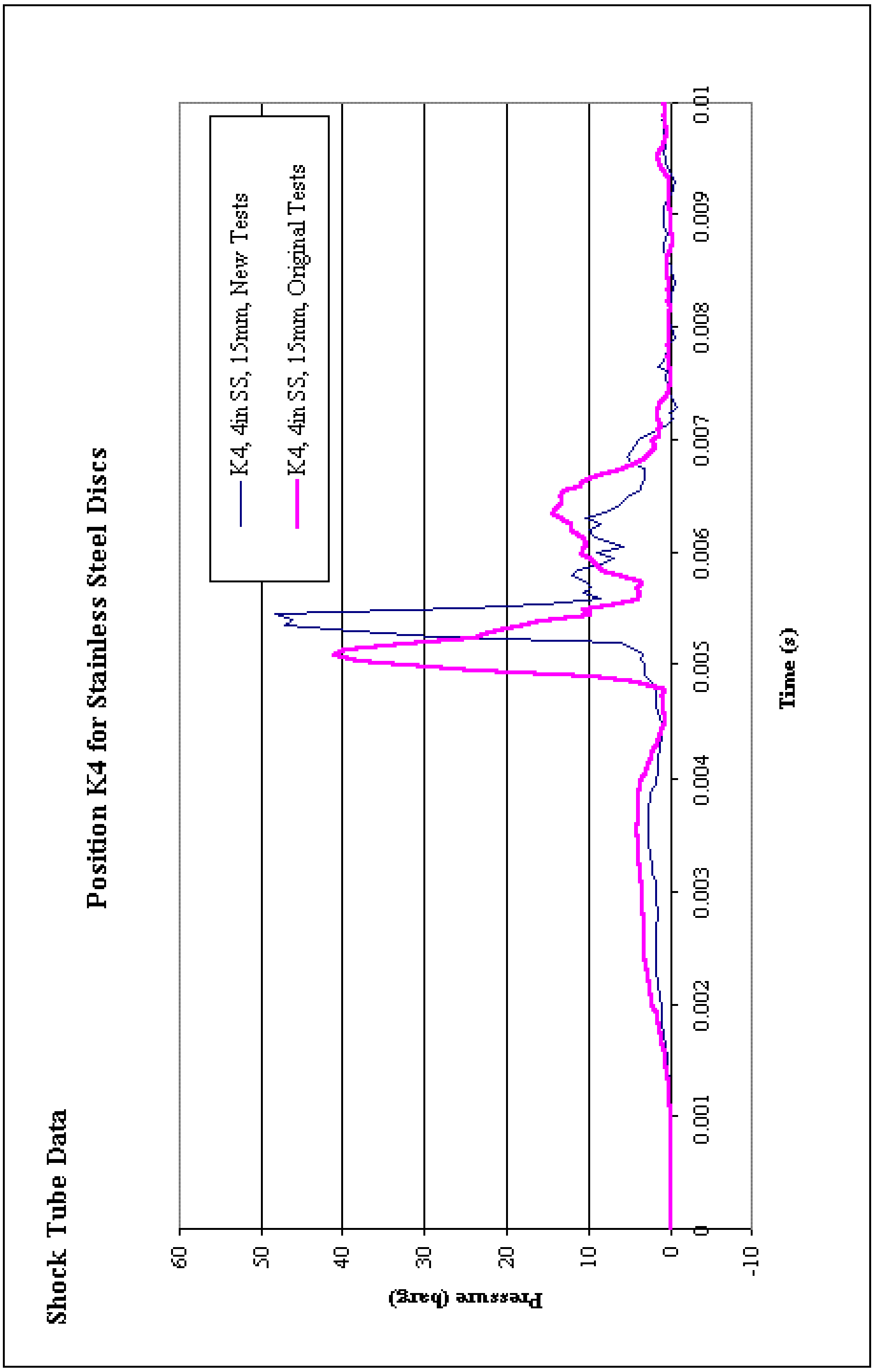

Figure 10 Measured Data - Comparing Burst Disc Tests (High Pressure)

7 STEEL BURST DISCS

7.1 INTRODUCTION

This section presents the findings from the tests on the stainless steel discs that were gained from the wider review of the previous tests and from the current experimental study and detailed analysis.

7.2 PREVIOUS TESTS - HIGH SPEED FILM CLIP

Our wider review of the previous data shows that high-speed filming of the stainless steel disc is the most informative. This gives a clear insight into the behaviour of the disc and we later show that the 8in disc was not compatible with the shock-tube performance (see Section 7.3).

Overall, the high-speed film clip comprises just over 2s of the burst disc sequence, approximately 1s of which is before the disc bursts. The recording rate was 4000 fps. Four key frames are shown on Figure 11 and Figure 12, together with a detailed description, but the events can be summarised as follows.

The steel disc is the reverse-buckling type and so the sequence starts with the steel disc in the concave position. As the clip progresses, the disc starts to distort; it then punches through into the convex position. Further deformation is apparent and then the disc starts to separate from the holder.

This particular device comprises a single, un-scored disc[11] and so this disc remains attached at the lower edge but then starts to peel away from the holder at the top. Thus at the end of the sequence, the disc presents as a flap of metal, attached only at the bottom and lying horizontally whilst a jet of water passes over it.

In some respects, the information on the film clip is not unexpected; as discussed later (Section 8.2) the performance of the steel disc is fundamentally different from the graphite disc. However, the most unexpected feature was the high level of deformation that was apparent before the disc separated from the holder. And in these test-conditions (i.e. with this 8in disc in the 4in shock-tube) the impact on the test results was significant. In particular, we believe that it may give erroneous information about the movement of the disc (see Section 7.3).

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[11] Other configurations include scored discs in which the discs burst with the four segments opening like petals

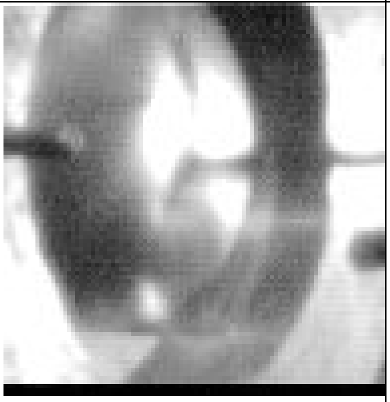
Film Clip	Frame No.	Time	Description
	4119	0 msec We have taken zero time to represent the beginning of the burst sequence	This frame is typical of the frames at the beginning of the clip. The clearest feature is the circular disc holder. The steel disc is the reverse-buckling type and so the face of the steel disc appears on the frame as the darker, concave shape.
	4165	11.5 msec	As the upstream pressure starts to rise, the disc starts to deform and then it inverts. This frame shows the disc at the stage when it has just 'punched through'. The disc face now appears convex.
	4186	16.75 msec	Once in the convex position, the disc does not immediately burst. Instead further deformation occurs. This frame shows the end of this sequence when the disc face is starting to separate from its holder.

Figure 11 Steel Disc Rupture - Clips 1, 2 & 3

Film Clip	Frame No.	Time	Description
	4230	27.75 msec	The disc is now bursting. The face of the disc is at about 30° to the vertical. Subsequent frames are dominated by the jet flow through the orifice Jet flow obscures the frames but it looks as if the disc is materially fully open by 55 msec

Figure 12 Steel Disc Rupture - Clip 4

7.3 BURST DISC INVERSION AND DEFORMATION

We are unable to make detailed calculations but we estimate that the inversion and deformation could change the volume at the disc by about 0.001 m^3. And although this is small in an industrial context, it is significant on the scale of the shock-tube, causing a de-pack effect.

Pack-in and de-pack are two phenomena that frequently develop in long distance pipelines and are therefore easiest to describe by considering a typical pipeline from a group of platform platforms delivering to landfall in the UK. For example, Figure 13 shows the pressure at the inlet to an onshore terminal after the closure of the main ESD valve. Flow into the terminal stops within minutes and this causes a corresponding pressure surge (up to about 30 barg), proportional to the local wavespeed and the velocity change in the pipeline.

This pressure rise is then transmitted upstream through the sub-sea pipeline, again at the local wavespeed and so over 5 minutes can elapse while the pressure-wave travels to the offshore platforms. But during this period, their export pressure is completely unaffected (Figure 14). This means that they continue to maintain their export rate and pack a volume of oil into the pipeline, despite the fact that there is no flow out of it, into the terminal (Figure 15).

This pack-in volume has the effect of increasing the average pressure in the pipeline. During normal operations, a typical export pressure from the platforms could be about 95 barg and the terminal pressure could typically be 5 barg, an average of 50 barg; and the pack-in would tend to increase the average. Moreover, the platforms can continue to pack the pipeline for 30 minutes or more until the high-pressure trips are activated and by this time the pressure throughout the system could exceed 100 barg.

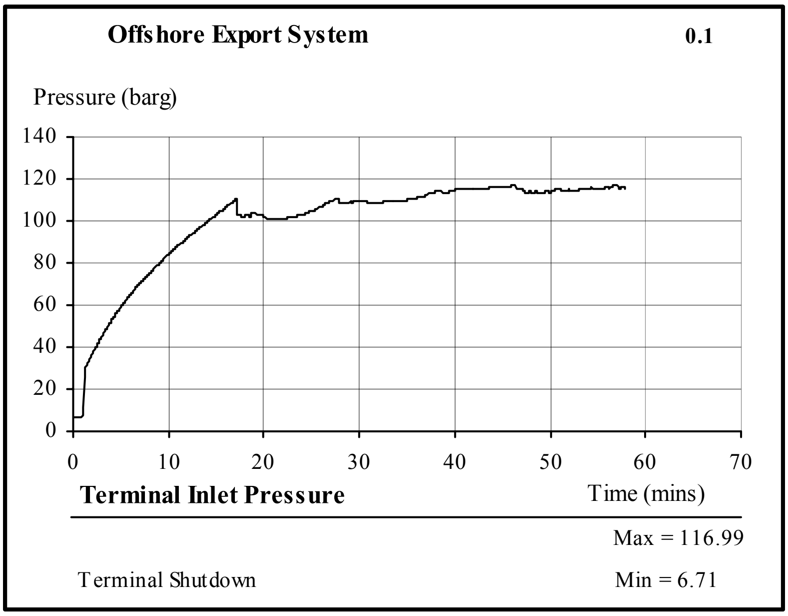


Figure 13 Pressure at the Onshore Terminal

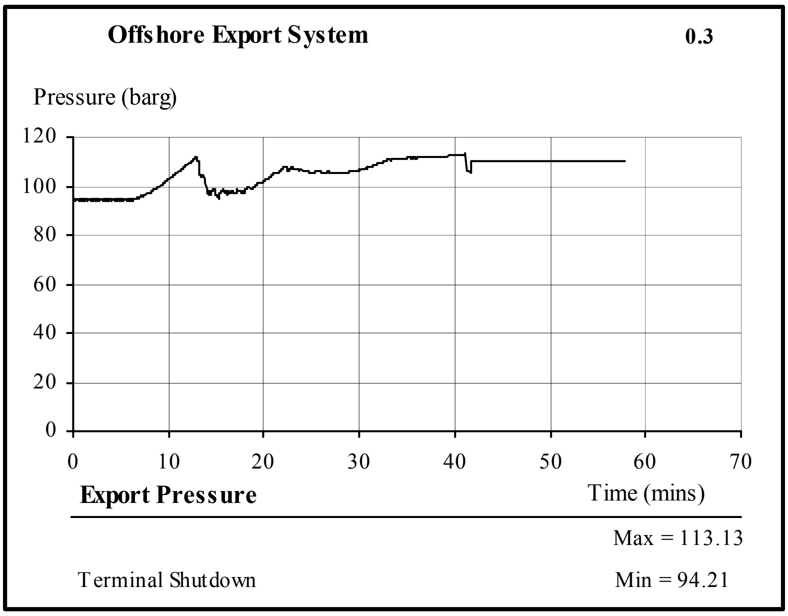


Figure 14 Pressure at the Offshore Platform

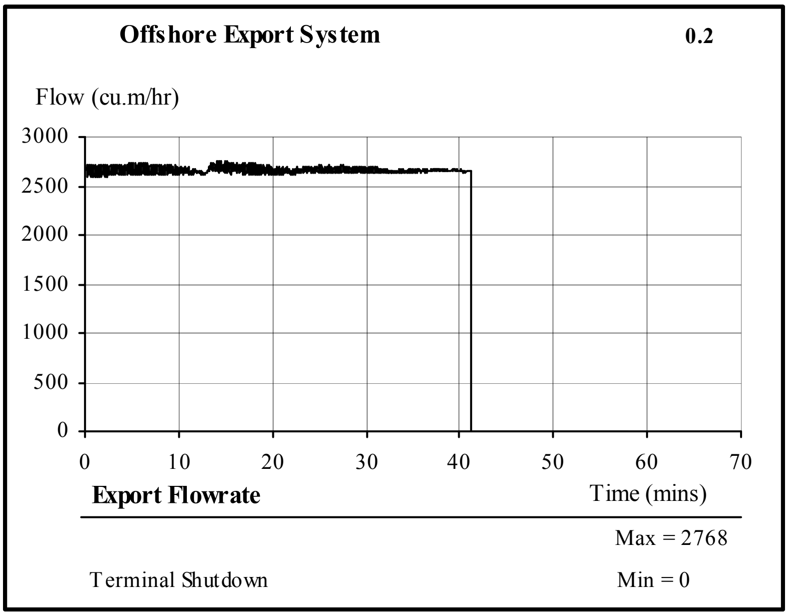


Figure 15 Flow from the Offshore Platform

Conversely, the pressure in the offshore system will drop back to the 50 barg average if the same volume of oil is taken out of the line (i.e. it is de-packed). And, although it is less intuitive and far less easy to visualise, we believe that this is the same phenomenon that is affecting the shock-tube results.

Our initial calculations suggest that the volume change that occurs at the steel disc (i.e. as it inverts and then deforms) is significant in the context of the shock-tube and is enough to de-pack the pressure. This means that, initially, the burst disc acts like an accumulator and hence its overall behaviour would comprise at least two phases i.e. accumulation and then relief.

7.4 PREVIOUS TESTS - REVIEW OF DATA FOR THE 8IN DISC

In the light of this finding, we examined the pressure measurements from the previous tests in detail and believe that they fully support this hypothesis. For example, the measured data for all three tests on the 8in steel disc is presented on Figure 17 and these all show that there are in fact three distinct stages (rather than two).

Together, the three stages generate a characteristic 'M' shaped pressure trace, shown for clarity on the reduced graph, Figure 16. Broadly, the actions in each of the three stages are inversion, deformation and rupture:

- Stage 1: The pressure at the disc initially rises above the burst pressure of the disc. This is enough to start the *inversion* process but the volume change causes localised de-pack effects and the pressure drops
- Stage 2: The disc acts like an accumulator. The pressure remains below the burst pressure whilst *deformation* occurs and the de-pack effect is more pronounced
- Stage 3: The disc is now fully deformed and so there is a sudden drop in the rate that the volume increases. This is similar to the effects seen with under-sized accumulators and the outcome is the same in that the pressure starts to rise rapidly. This now causes the disc to *rupture*; the metal flap separates from the holder, the burst flow develops and the pressure drops quickly to zero. In this stage, the peak pressure may exceed the original peak, seen in Stage 1.

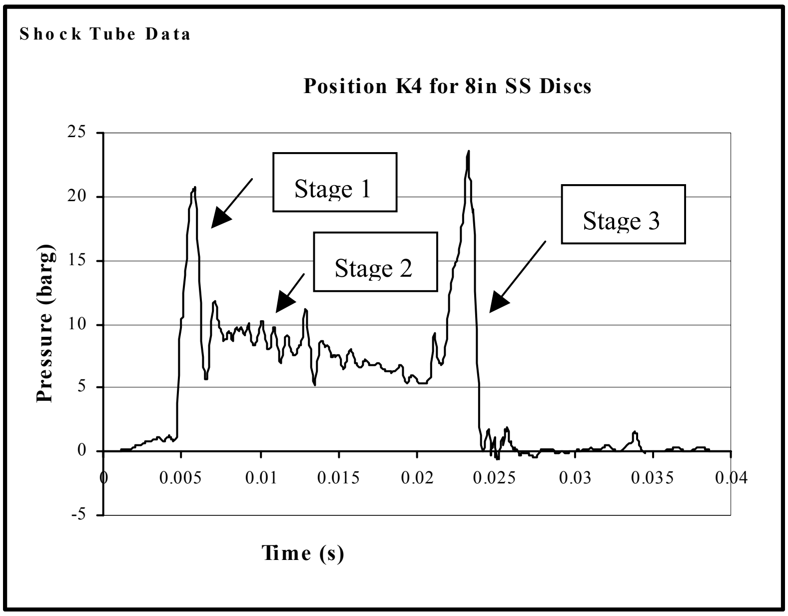


Figure 16 Measured Data - 8in Steel Disc (Medium-Pressure Test)

The measured data also suggests that in the worst case (i.e. the low-pressure test), the 8in disc takes about 45 msec to rupture (Figure 17) but we believe that this is a function of the test conditions and is not representative of the performance in the field. This de-pack effect is exaggerated because an 8in disc is tested on a 4in shock-tube.

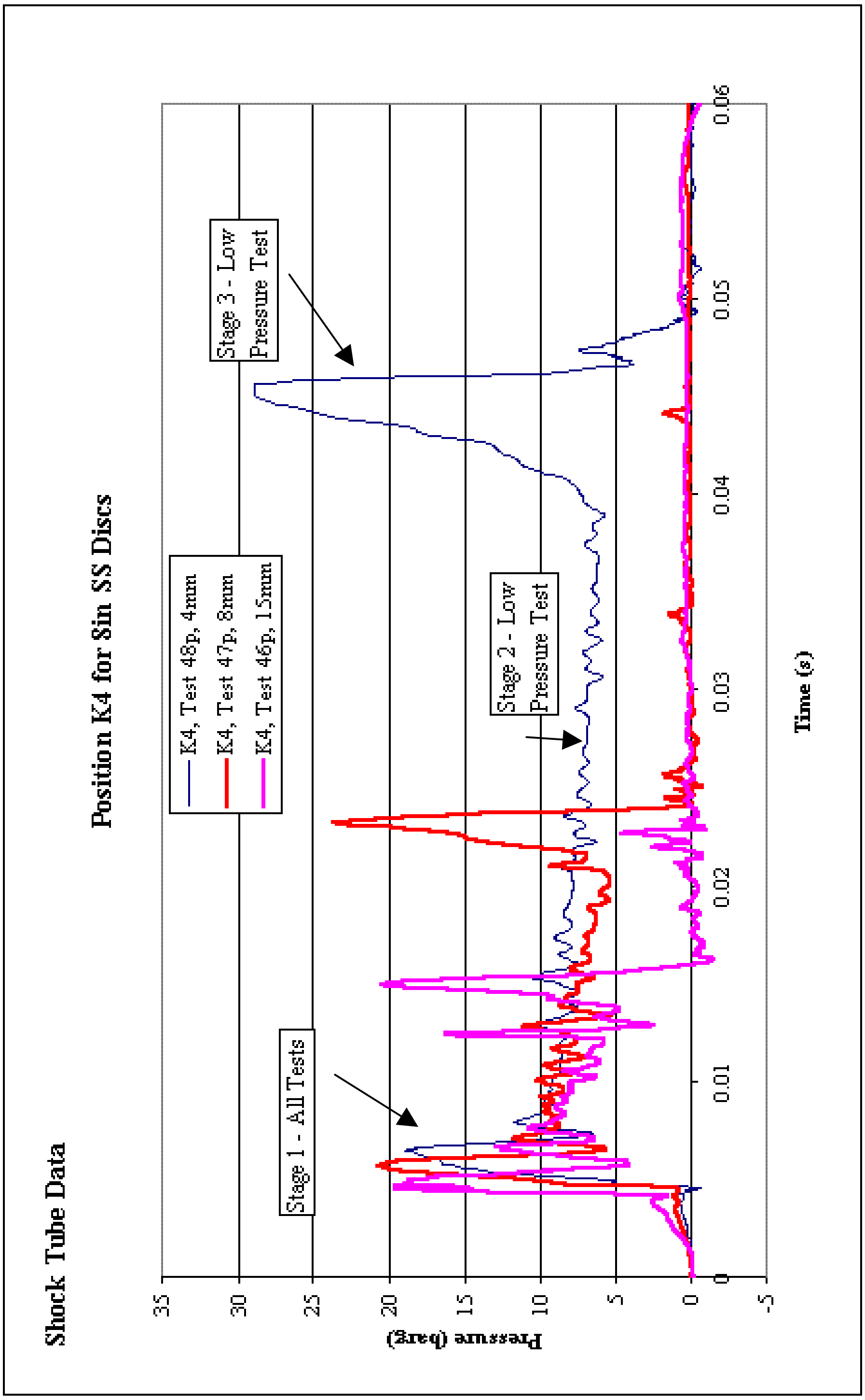


Figure 17 Measured Data - 8in Stainless Steel Disc

7.5 NEW EXPERIMENTAL TESTS

The 8in disc was badly over-sized in the context of the shock-tube and so it is possible to argue that the inversion/deformation effect is interesting, but over-exaggerated. The new experimental tests therefore tried to eliminate the dominance of these effects by using test-conditions that were more compatible.[12]

However, examination of the results shows that the three characteristic stages (inversion, deformation and rupture) are also apparent in the new tests (Figure 18 and Figure 19). The main difference is that the duration of the 3-stage response is shorter with the smaller discs (Table 9). In the medium-pressure test, for example, the elapsed time for the 3in disc is only 11.8% of the time for the 8in disc; the time for the 4in disc is 20.5% of the 8in disc.

Table 9 Measured Data - Duration of 3-Stage Characteristic Response

Test	3in Disc	4in Disc	8in Disc
Low-Pressure	4.80 msec	7.65 msec	45.05 msec
Medium-Pressure	2.15 msec	4.05 msec	19.80 msec
High-Pressure	1.40 msec	2.45 msec	11.75 msec

These results were analysed further and all the tests showed two key features:

- The duration of the 3-stage response is approximately related to the size of the disc and the volume occupied by the reverse-buckling configuration
- The volume changes (associated with the discs inverting and deforming) are still big enough to de-pack the shock-tube and lower the local pressure.

We therefore conclude that, even though the discs that were tested in this phase of the study are smaller (3in and 4in), their rupture time is adversely influenced by the test conditions. And this means that the findings must be viewed cautiously.

This need for caution is exemplified on Figure 20, which compares the performance of the 4in steel disc with a 4in graphite disc.[13] Superficially, this suggests that the steel disc is capable of the very fast rupture time predicted for the graphite disc in the previous study (i.e. 1.9 msec). But in practice only the graphite disc has ruptured in this time; the steel disc has reduced the pressure by the de-pack effect and the actual rupture occurs a few milliseconds later.

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[12] See Section 4

[13] These test results are taken from the previous study. A slight offset is apparent on the time-scale but otherwise, the magnitude and period of the first pressure-peak are materially identical

Overall, this means that we cannot obtain reliable rupture times for the steel discs from this study for use in typical industrial applications.[14] However, some significant relationships are apparent. We believe the rupture time will depend on the size of the disc and also the rate of change of the local pressure. The capacity of the adjacent piping may also be a factor (as this dictates the magnitude of the de-pack effect) but this should not be significant in normal applications.

7.6 CONCLUSIONS

Our conclusions on the steel burst discs are summarised, together with the graphite burst discs in Section 8.6.

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[14] In terms of the previous study however, we remain confident that the steel discs will be capable of the fast action needed in the event of a tube rupture on the high-pressure side of a heat exchanger

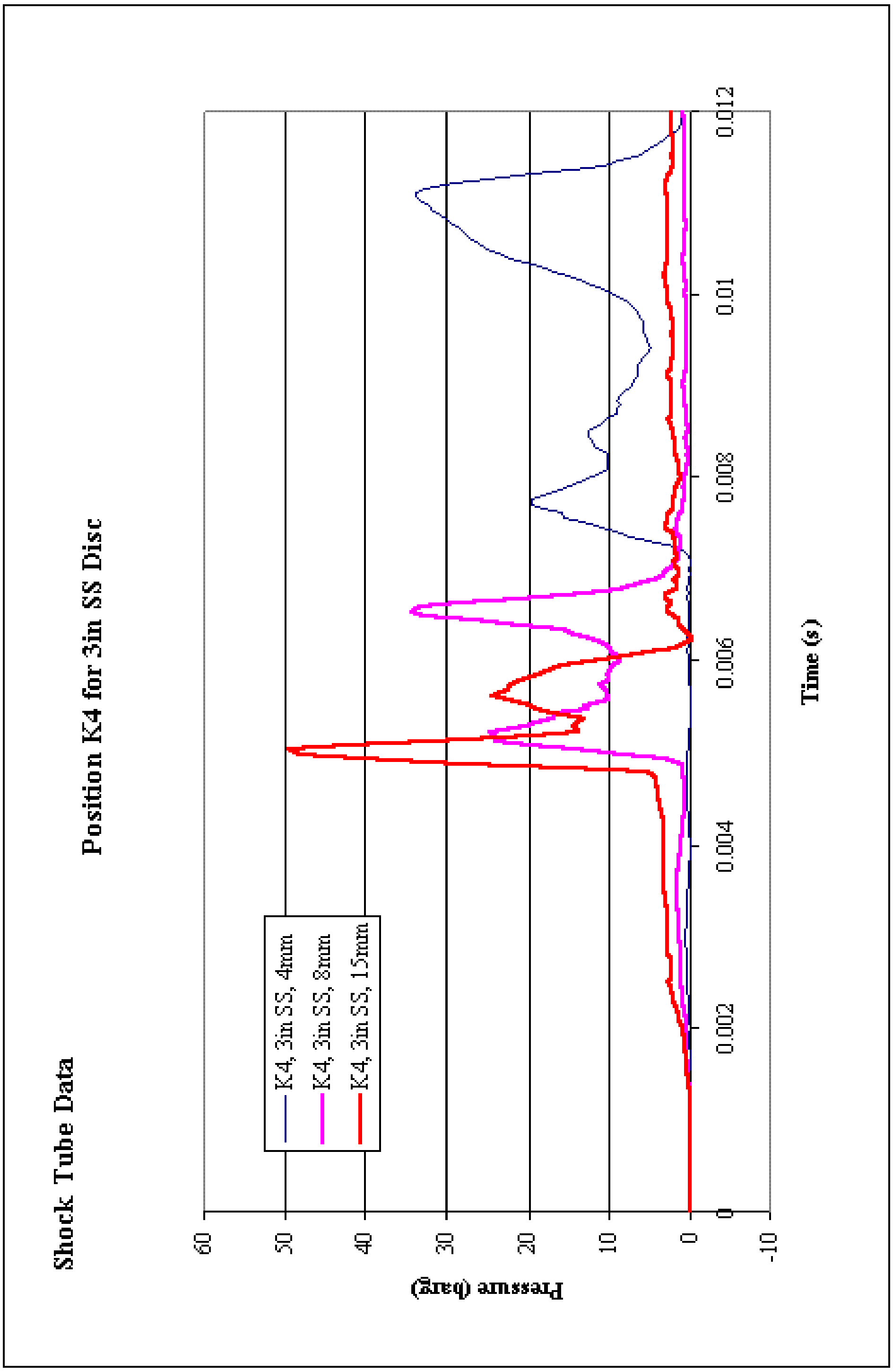


Figure 18 Measured Data - 3in Stainless Steel Disc

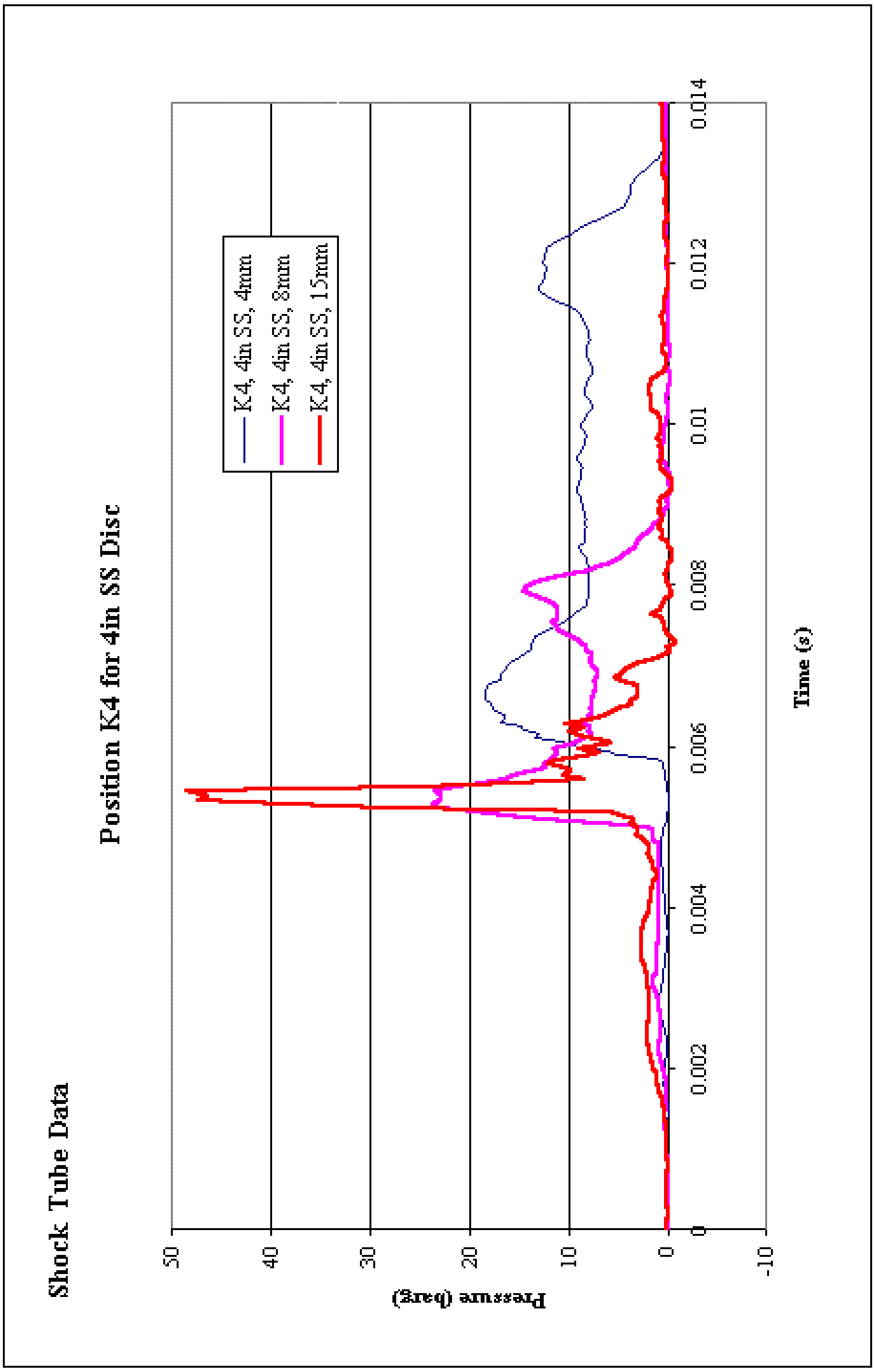


Figure 19 Measured Data - 4in Stainless Steel Disc

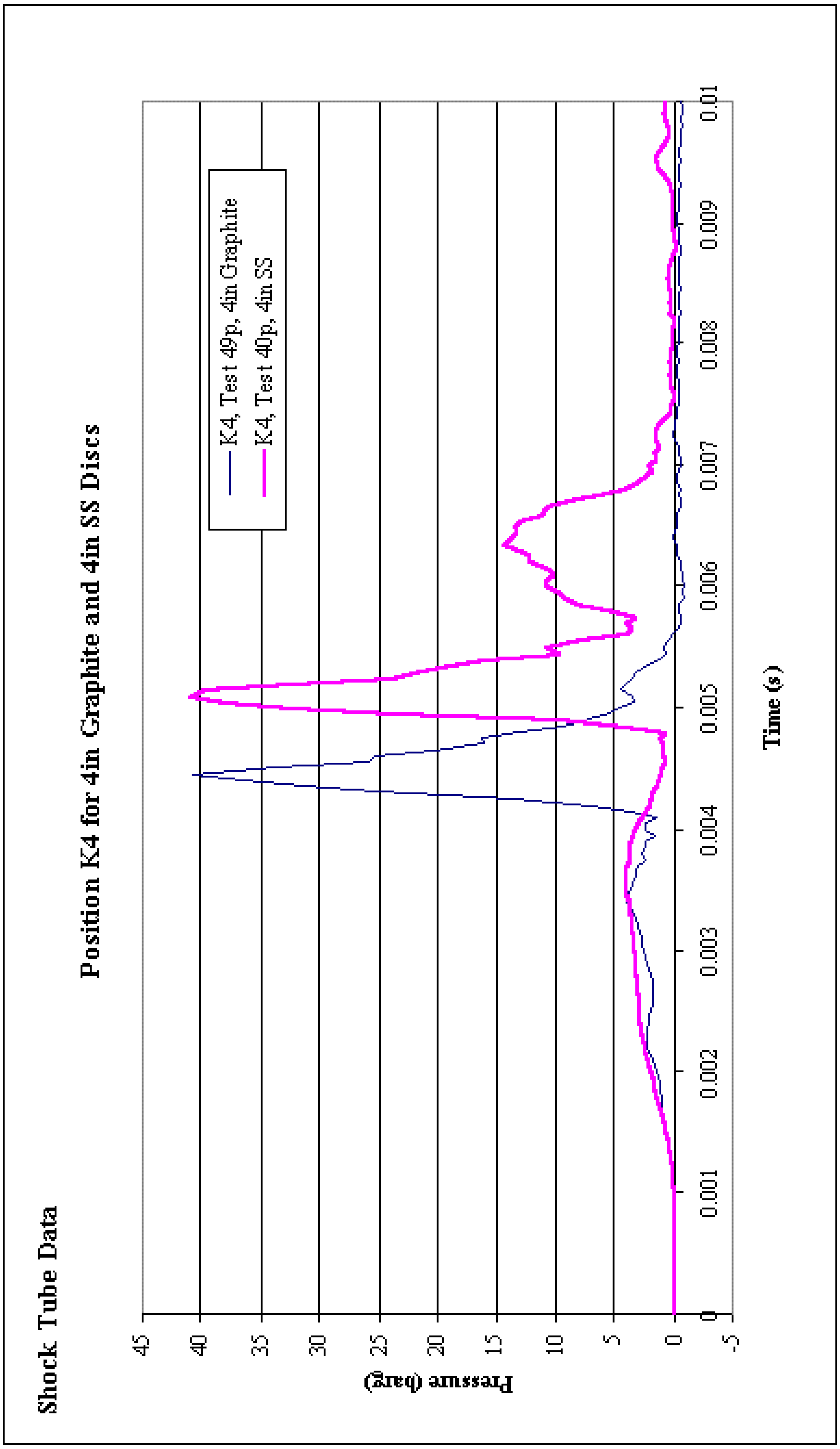


Figure 20 Measured Data - 4in Graphite and Steel Discs

8 GRAPHITE BURST DISCS

8.1 INTRODUCTION

This section discusses the results and findings on the graphite burst discs. The high-speed film from the previous tests is examined first, followed by the pressure measurements and detailed analysis.

8.2 PREVIOUS TESTS - HIGH SPEED FILM CLIP

The high-speed film clip again comprises just over 2s of the burst disc sequence, approximately 1s of which is before the disc bursts. The recording rate was 4000 fps. Four key frames are shown on Figure 21 and Figure 22, together with a detailed description but the events can be summarised as follows.

The graphite disc is a flat-faced type and so the sequence starts with the face in a 'neutral' position. As the clip progresses, some slight distortion is apparent on the face of the disc but, within 2.75 msec it starts to distort and shatter at the centre.[15] The next frames show that the shattering develops further; thus the complete disc has been swept into the downstream piping in less than 10 msec and it offers no further restriction to flow.

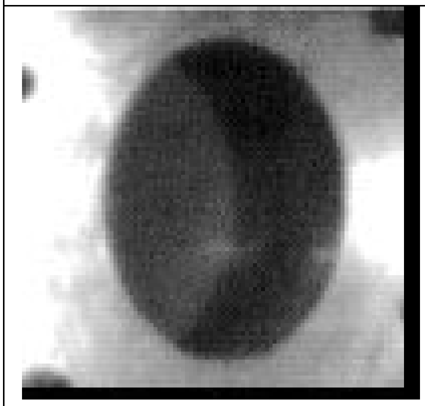
Film Clip	Frame No.	Time	Description
	4116	0 msec We have taken zero time to represent the beginning of the burst sequence	This frame is typical of the frames at the beginning of the clip. The clearest feature is the circular disc holder. The graphite disc is the flat-faced type and so the face of the disc appears on the frame as the darker, flat shape at the back of the circle.

Figure 21 Graphite Disc Rupture - Clip 1

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[15] This is completely different from the performance of the steel disc (discussed earlier) which starts to distort, then inverts into the convex position, deforms and then separates from the holder.

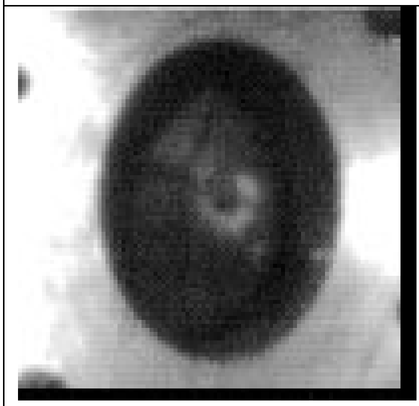
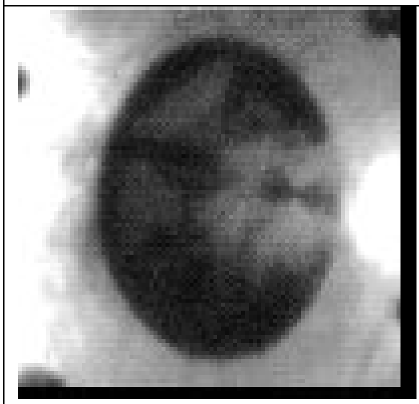
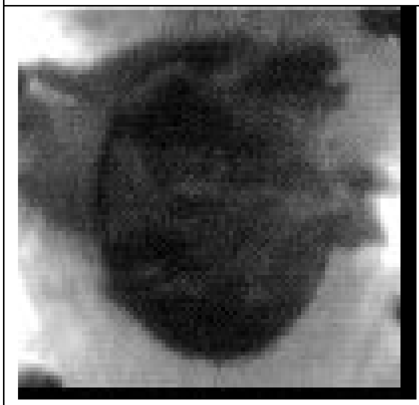
Film Clip	Frame No.	Time	Description
	4127	2.75 msec	As the upstream pressure starts to rise, the disc starts to distort at the centre and it becomes slightly convex.
	4136	5 msec	Unlike the steel disc, there is no obvious period of deformation and invertion. The disc starts to deform and then, within another 2 msec, the centre has shattered and flow develops.
	4150	8.5 msec	The disc has almost completely shattered and jet flow is developing across the full diameter

Figure 22 Graphite Disc Rupture - Clips 2, 3 & 4

The information on the film clip confirms that the performance of the graphite disc is fundamentally different from the steel disc (see also Section 7.2):

- The graphite disc shatters almost as soon as the burst pressure is passed and the fragments of the disc are swept into the downstream piping
- The steel disc inverts fully and then the disc separates from the holder like a flap of metal. And as seen during the testing, the disc can open fully or remain only partially opened, depending on the test-pressure

8.3 PREVIOUS TESTS - REVIEW OF MEDIUM AND HIGH PRESSURE TESTS

None of the tests for the 6in graphite disc had been studied previously and neither had the medium pressure test for the 4in disc (i.e. with the 8mm orifice) and so we have examined these, in particular comparing them with the tests we had analysed previously.

For example, the previous study showed excellent correlation between the measured results and the computer analysis (Figure 23) for the 4in disc in the high-pressure test, with a burst time of 1.9 msec. And this gives a benchmark for the performance of the discs of other sizes and pressure conditions. However, the film clip has already shown that the 6in disc opened more slowly in the medium-pressure test (< 10 msec) and so this indicates that the response may be related to size and/or overpressure.

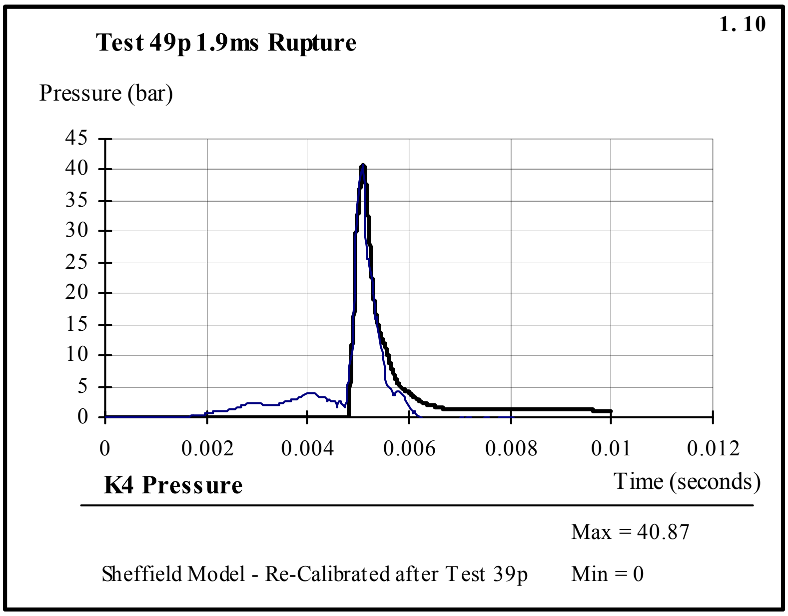


Figure 23 Correlation for Graphite Disc, High Pressure Test

The measured results for this high-pressure test and the medium-pressure test on the 4in disc are therefore compared on Figure 24. Broadly, these results are similar but slight differences in the way that the pressure decays after the disc has ruptured suggest that the rupture time is slightly slower at lower pressures.

Our benchmark for this comparison is the point at which the pressure drops to zero after the disc burst because this indicates that the device is no longer restricting flow. We define this as the time taken for the device to be 'effective'. The pressure and disc capacity are no longer linked once the pressure has dropped to zero (i.e. the pressure becomes insensitive to the disc area) and so it is impossible to predict the subsequent behaviour of the device. And that is why this part of the study has compared the time taken for the disc to be 'effective', rather than the burst times.

For example:

- For the high-pressure test, the 4in graphite disc is 'effective' by a measured time of 0.0055s. when the pressure drops to zero
- In contrast, this effect occurs slightly later and more slowly in the medium-pressure test.
- Similarly, Figure 25 shows that the 6in disc is also slightly slower than the 4in disc in the high-pressure test

But despite these differences, the burst discs have been 'effective' within 2.4 msec in all three cases i.e. the pressure has dropped to zero.

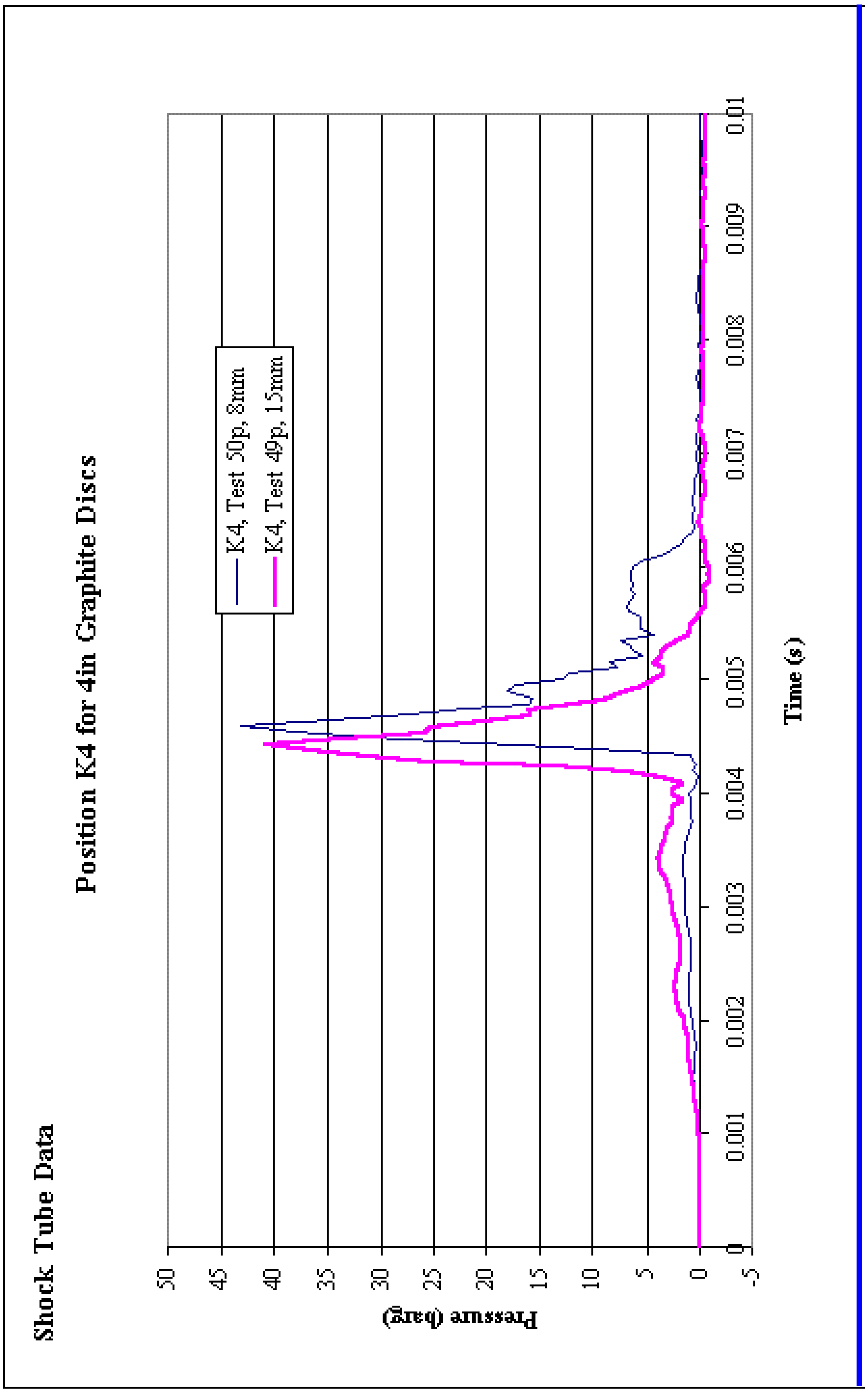


Figure 24 Measured Data - 4in Graphite Disc

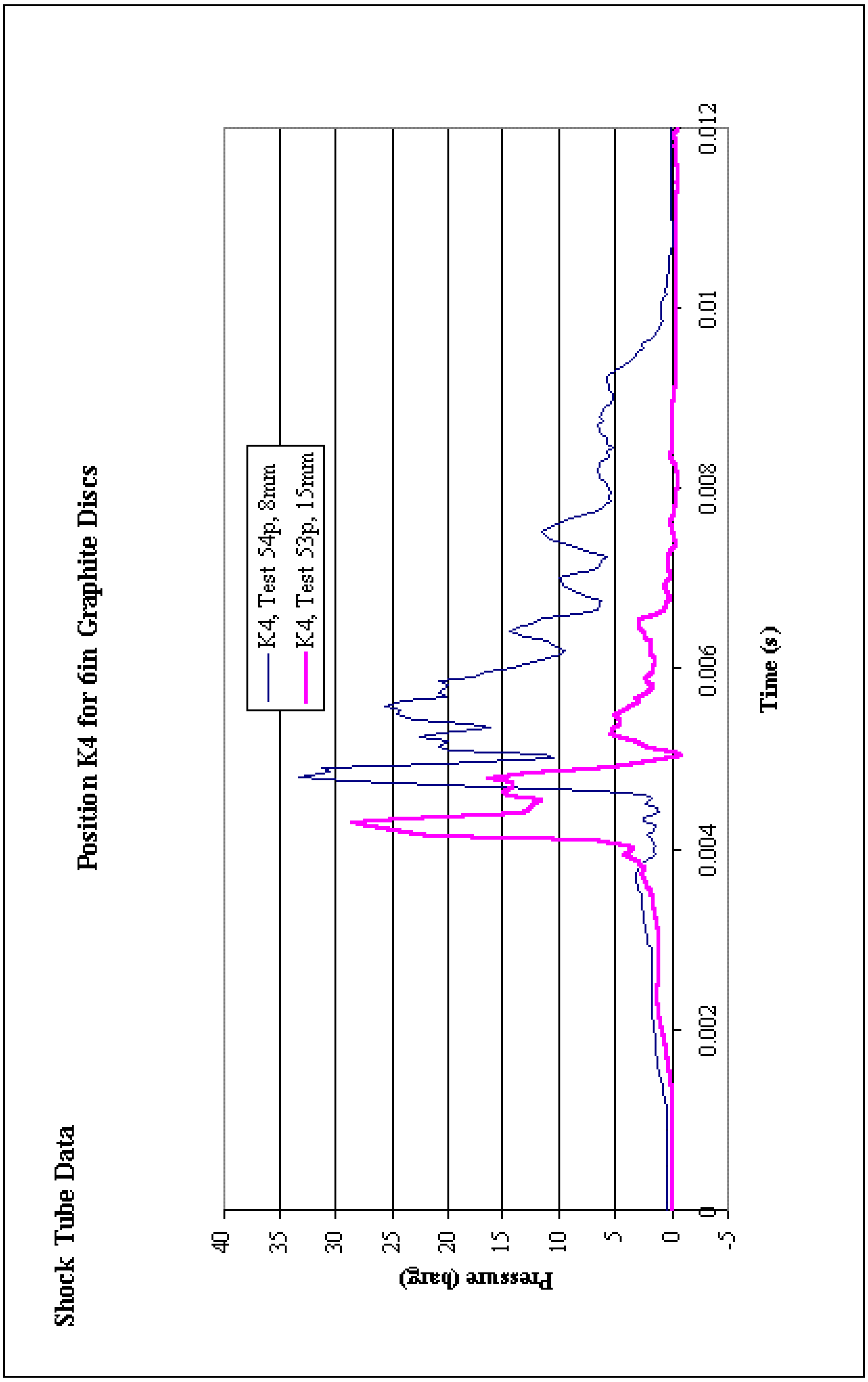


Figure 25 Measured Data - 6in Graphite Disc

The trend is slightly different for the 6in disc in the medium-pressure test (Figure 25) with the performance more like the slower response in low-pressure tests (see Section 8.4) than the high-pressure ones. This also suggests that the burst time is related to both size and the amount of overpressure but, even so, our interpretation of the pressure measurements suggests that the disc is 'effective' within 6 msec.

This comparison has also highlighted a limitation of the study i.e. in the need to compare the time for the burst discs to be 'effective.' The pressure and disc capacity are no longer linked once the pressure has dropped to zero (i.e. the pressure becomes insensitive to the disc area) and so it is impossible to predict the subsequent behaviour of the device.

Despite this qualitative approach, more information can be gained from the observations from the film clip for the 6in disc in the medium-pressure test (see Section 8.2).[16] This showed that the disc started to distort after 2.75 msec and was passing flow within 5 msec. This is therefore in complete agreement with estimate above i.e. that the 6in disc was fully effective within 6 msec. And, from the film clip we also know that the disc had shattered completely within 10 msec.

8.4 PREVIOUS TESTS - LOW PRESSURE

So far, this examination of the previous data has concentrated on the high and medium pressure tests where the discs are subjected to excessive pressures, potentially over four times the rupture pressure. In contrast, the potential overpressure would be significantly lower in many offshore piping applications and so we have re-examined the low-pressure test results.

The pressure measurements at K4 are presented on Figure 26 for both the 4in and 6in graphite disc. Again using the 'effective' benchmark, the figure shows that the time taken for the pressure wave to reduce to zero is 4.5 msec for the 4in disc and 6.8 msec for the 6in disc. Thus the discs are slower under moderate pressure conditions but the burst time is still in line with the value of 10 msec time that is frequently quoted.

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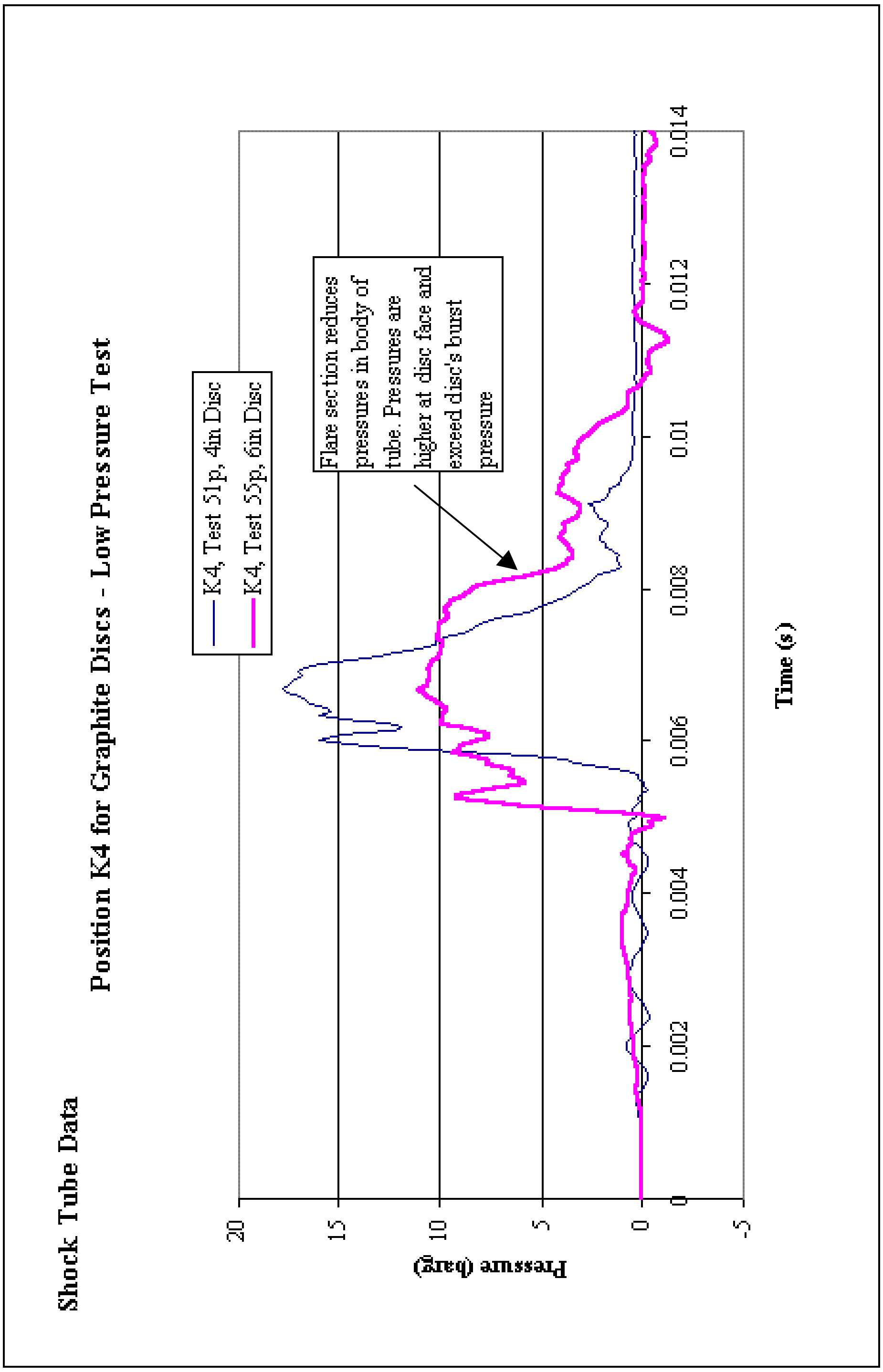
[16] This showed the 6in graphite disc in the medium-pressure test



Flare section reduces pressures in body of tube. Pressures are higher at disc face and exceed disc's burst pressure

Figure 26 Graphite Disc Performance (Low-Pressure Tests)

8.5 NEW EXPERIMENTAL TESTS

As noted in Section 4.4, reverse-buckling graphite discs were selected for the new test programme but the results were inconclusive. The aims had been:

- To establish whether the shape/configuration would prove to be a significant parameter, as seen with the steel discs.
- To allow fair comparison between the steel and graphite discs

Commercially, the flat-faced (machined) discs can be supplied with maximum bursting pressures of typically 14-20 barg[17] but reverse-buckling discs are made from compressed graphite and the bursting pressures are correspondingly reduced (2.5-4.5 barg). And our detailed analysis of the results shows that this proved to be the dominant factor, outweighing any impact of the volume-effect seen with the steel discs. In fact, the low burst-pressure of the 4in disc caused problems when the tests were being set up; discs were shattered while eliminating air bubbles from the water-filled shock-tube. And the low-pressure tests show the typical trends of air entrapment (within the facility) had re-occurred.[18]

Despite these problems, the new experimental tests provide two significant areas of information. Firstly, they support the findings to date. They show that the graphite bursting discs are slower under moderate pressure conditions but still provide fast-acting relief and, as shown on Figure 27, the discs are effective in less than 10msec. This is therefore still in line with (and supportive of) the values in the original IP study.

The second area of information relates to the way in which the burst discs shatter. The steel discs show a characteristic 3-stage response as the metal distorts but the graphite discs do not exhibit this phenomenon, even when the reverse-buckling types are tested (Figure 28).[19]

Based on this finding and our previous results, we therefore believe that the performance shown on the film clip is probably representative of all types of graphite disc (see Section 8.2). Some slight distortion may start to occur at the centre of the disc but it will not invert and then deform. Instead it will start to shatter at the centre and the shattering will then develop further until the complete disc has been swept into the downstream piping.

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[17] The typical maximum bursting pressure of a 4in graphite disc is 14 barg and 20 barg for a 3in disc

[18] These had been identified in the early stages of the previous study and test procedures were established to eliminate them (e.g. inclining the shock-tube and the use of surfactant), see Section 5.4

[19] The purpose of this figure is only to compare the shape of the pressure wave. The magnitude cannot be compared because the burst pressure of the steel disc is 14.6 barg and the graphite disc is only 3.6 barg. But to obtain reasonable parity, this figure shows the pressure ratio i.e. the measured pressure divided by the burst pressure for each disc

8.6 CONCLUSIONS - GRAPHITE AND STEEL DISCS

High-speed films were taken of the burst discs and these provided additional insight into the performance of the burst discs. Firstly they confirmed that the performance of the steel disc is fundamentally different from the graphite disc:

- The graphite disc shatters almost as soon as the burst pressure is passed and the fragments of the disc are swept into the downstream piping (see also)
- The steel disc inverts fully and then the disc separates from the holder like a flap of metal. And as seen during the testing, the disc can open fully or remain only partially opened, depending on the test-pressure

However, the film-clip then provided an important finding which had not been anticipated and this was the high level of deformation that was apparent before the steel disc separated from the holder. Moreover, our calculations show that the volume changes that accompany this deformation are significant in the scale of the shock-tube, even for the 3in disc. This means that, initially, the burst disc acts more like an accumulator and hence its overall behaviour comprises two phases i.e. accumulation and then relief.

This was confirmed by our detailed assessment of the pressure measurements and, in the worst case, it also showed the 8in disc taking over 40 msec to rupture but we believe that this is a function of the test conditions and is not representative of the performance in the field. This accumulation effect is exaggerated because an 8in disc is tested on a 4in shock-tube.

Our detailed analysis shows that the 3in and 4in discs are apparently capable of faster action (i.e. faster than the 40msec quoted above). However, we have major reservations in stating exact times; the deformation effect is not so severe for the smaller discs but we cannot totally discount its impact. In turn, this reduces the applicability of our findings.

In contrast, the results for the graphite discs are more reliable. The study shows that the rupture time is related to both size and overpressure. But, even at the lowest levels of overpressure that we studied, the disc is a fast acting relief device. The findings from the film clip, from the tests and from the manufacturers' data all give rupture times of less than 10 msec and are therefore still in line with (and supportive of) the values in the original IP study.

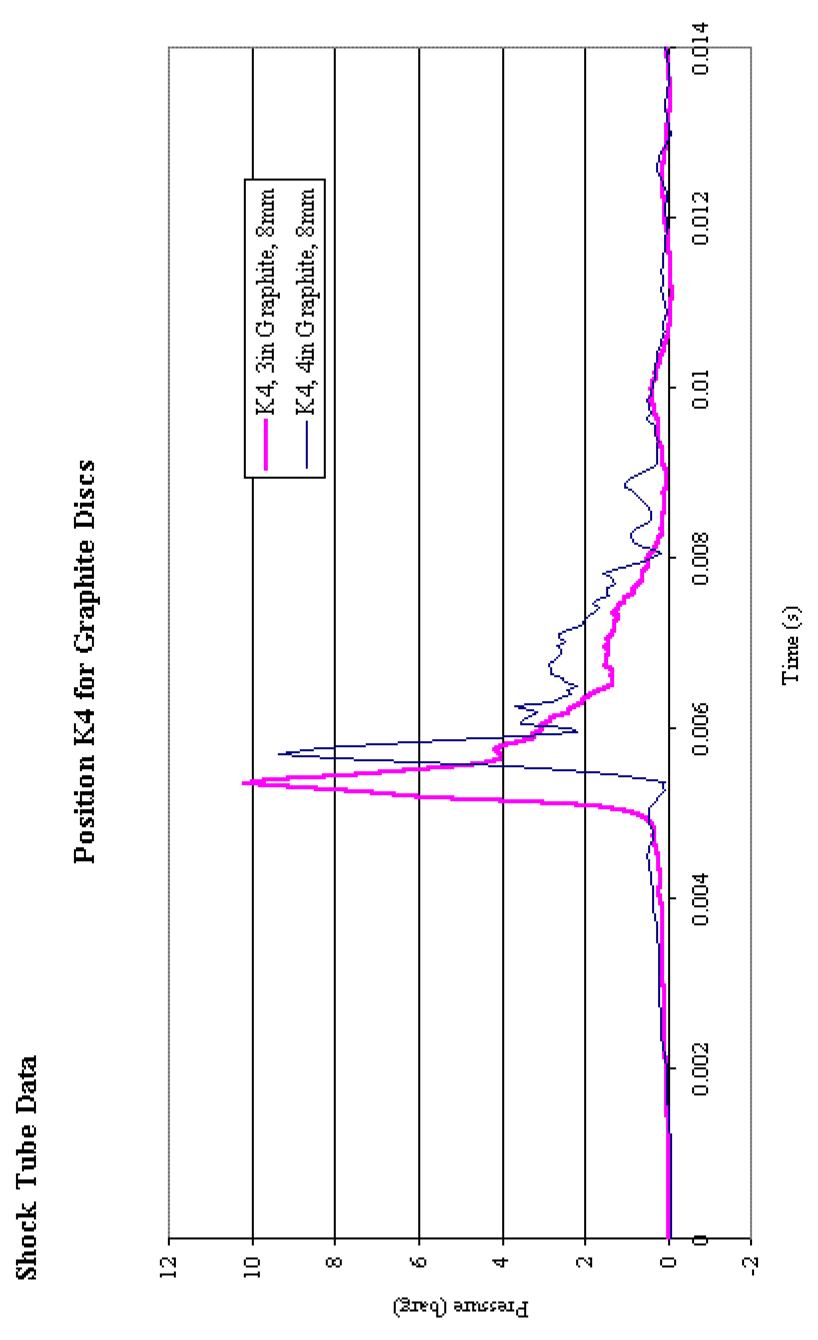

Figure 27 Measured Data - 3in and 4in Graphite Discs

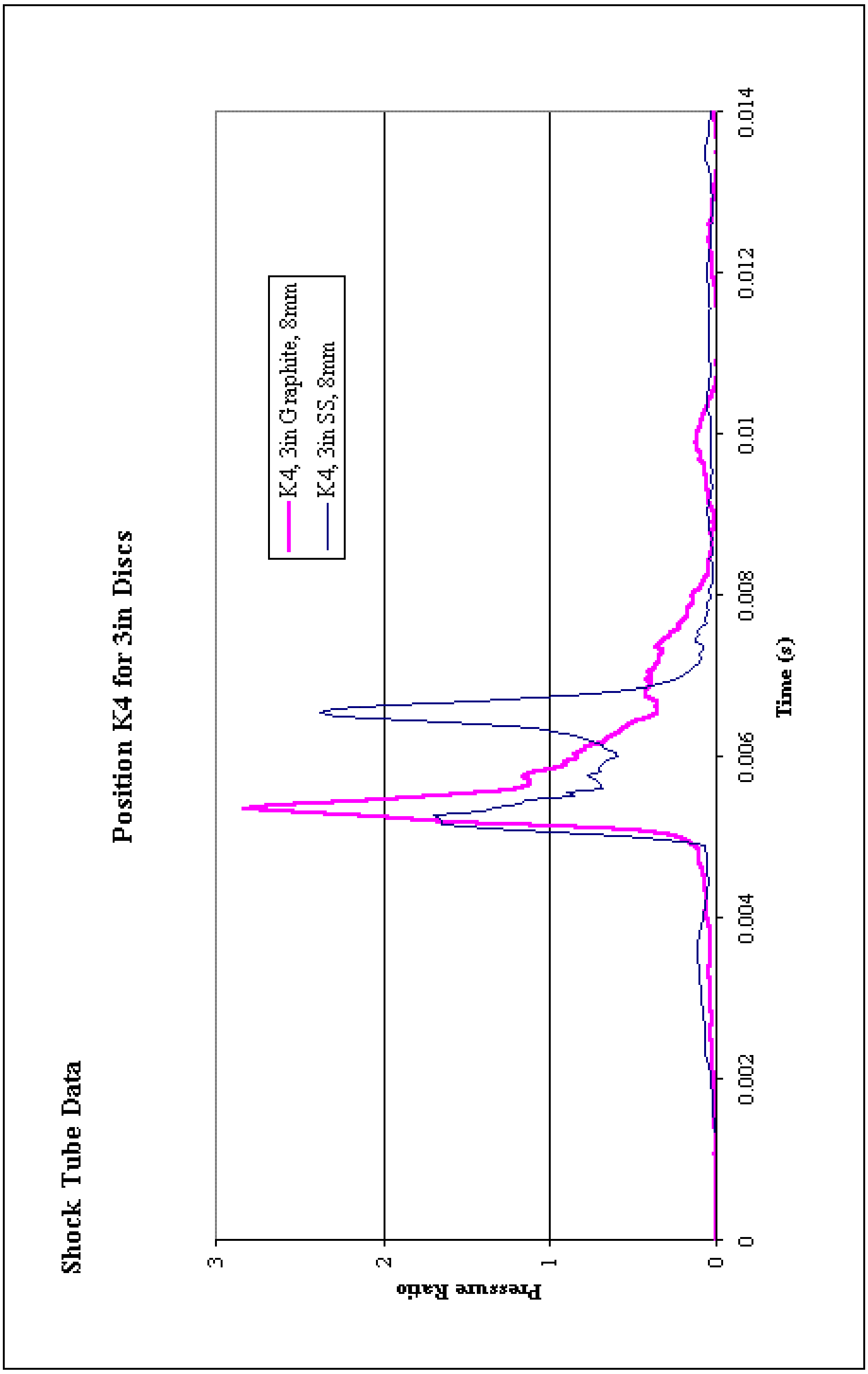

Figure 28 Measured Data - Comparing 3in Burst Discs (Medium Pressure)

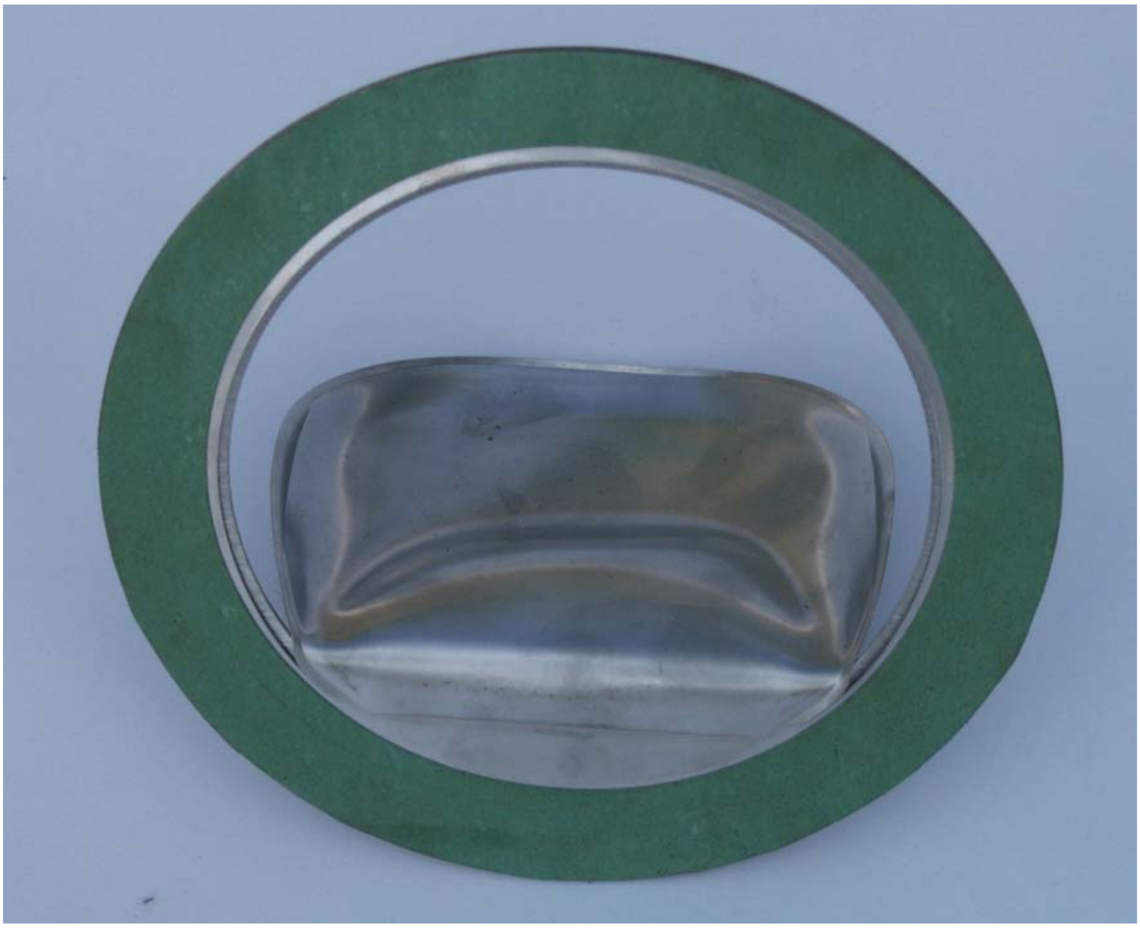

Figure 29 Picture of 4in Steel Burst Disc at Completion of Test

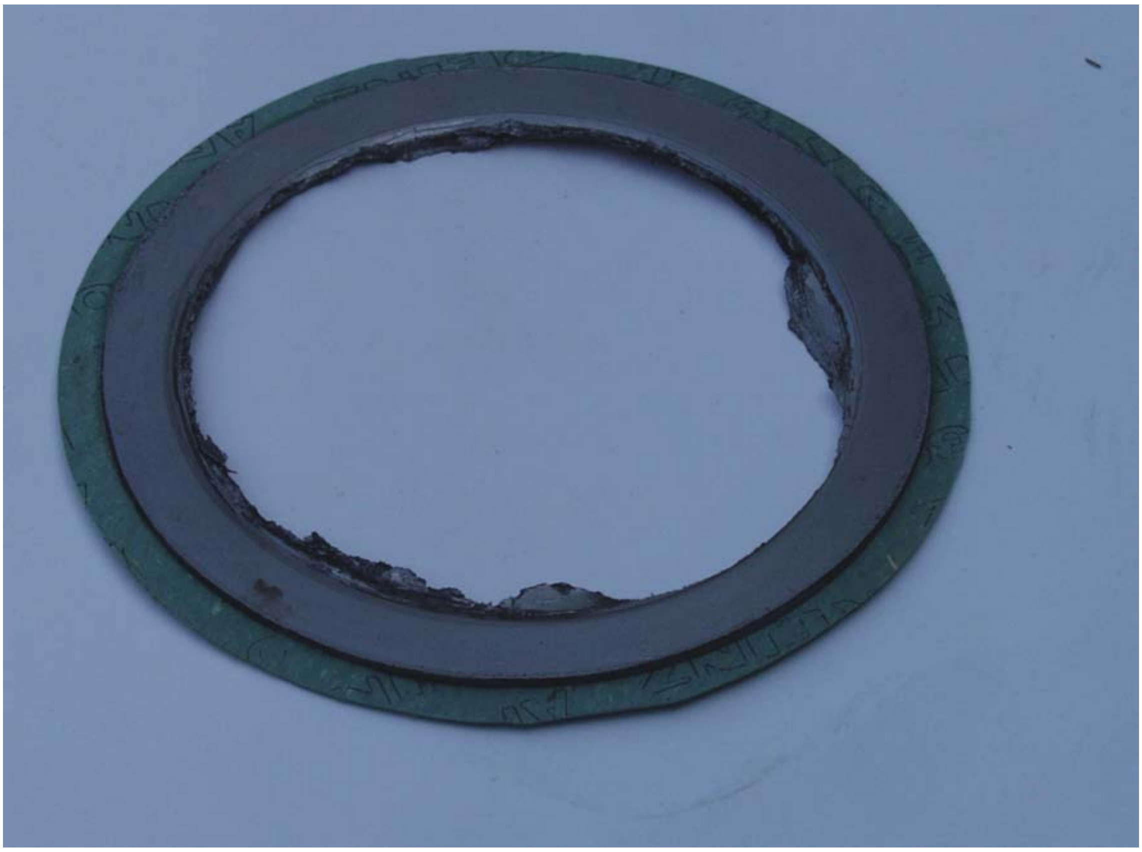

Figure 30 Picture of 4in Graphite Burst Disc at Completion of Test

9 SAFETY AND RELIEF VALVES

9.1 INTRODUCTION

The previous study suggested that the opening time of the SRVs was similar to that of the graphite burst discs. These findings were supported by the very high level of correlation between the measured and simulated data and also by inspection of the pressure measurements. But they were completely unexpected;[20] they do not agree with the data given in the IP Guidelines of 80-350 millisec and are faster than the tested value of 25 msec by Kruisbrink, 1990.[21]

One of the objectives of this review and re-testing of the SRVs was therefore to determine whether it provided any further information on this issue. In particular we had noted that the SRV in the previous study was small (2H3), it was subjected to a significant overpressure and it was the pop-action type. Subjectively, we expected the opening times to be at the fast end of any performance range and suggested that further work should be undertaken to determine whether the findings were related to size or pressure. This section therefore discusses the findings in detail.

9.2 DEFINITIONS

Throughout this study, the valves are defined in line with industry conventions as follows:

- Safety Valves (SRVs): Valve action is characterised by rapid opening or pop action
- Relief Valves (RVs): The valve lifts in proportion to the pressure increase over the opening pressure

The rated capacity of a SRV/RV is reached when it is 10% overpressure i.e the inlet pressure is 110% of the set pressure. We have therefore defined the opening time of the valves as the time taken to reach the rated capacity.

9.3 PREVIOUS STUDY - SPRING LOADED SRV

In our wider review of the previous tests, the high and medium-pressure tests were compared for the SRV to see whether a pressure-relationship could be seen. In particular we were interested in the amount of time that elapses between the pressure starting to rise and it peaking.

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[20] We therefore recommended that the finding should therefore be treated with extreme caution until further work has been undertaken to investigate this further and to establish points of comparison.

[21] Modelling of Safety and Relief Valves in Waterhammer Computer Codes, Kruisbrink, A.C.H., Proc. 3rd Int. Conf. Valves and Actuators, BHR Group, STI 1990

And Figure 31 shows that this period is almost 60% longer in the medium-pressure case, immediately supporting the hypothesis that the very fast action was directly related to the high level of overpressure on the valve.

We therefore undertook a detailed analysis on the simulation model to establish the relationship between the peak pressures and the opening time of the SRV. And from this, we calculated an opening time for the medium-pressure test that was 25% slower than the value determined for the high-pressure test in the previous study.

Table 10 Opening Times for Small SRV (2H3)

Device	**Test Condition**	**Opening Time (msec)**
Conventional Spring Loaded SRV (2 H 3)	High Pressure	4
	Medium Pressure	5

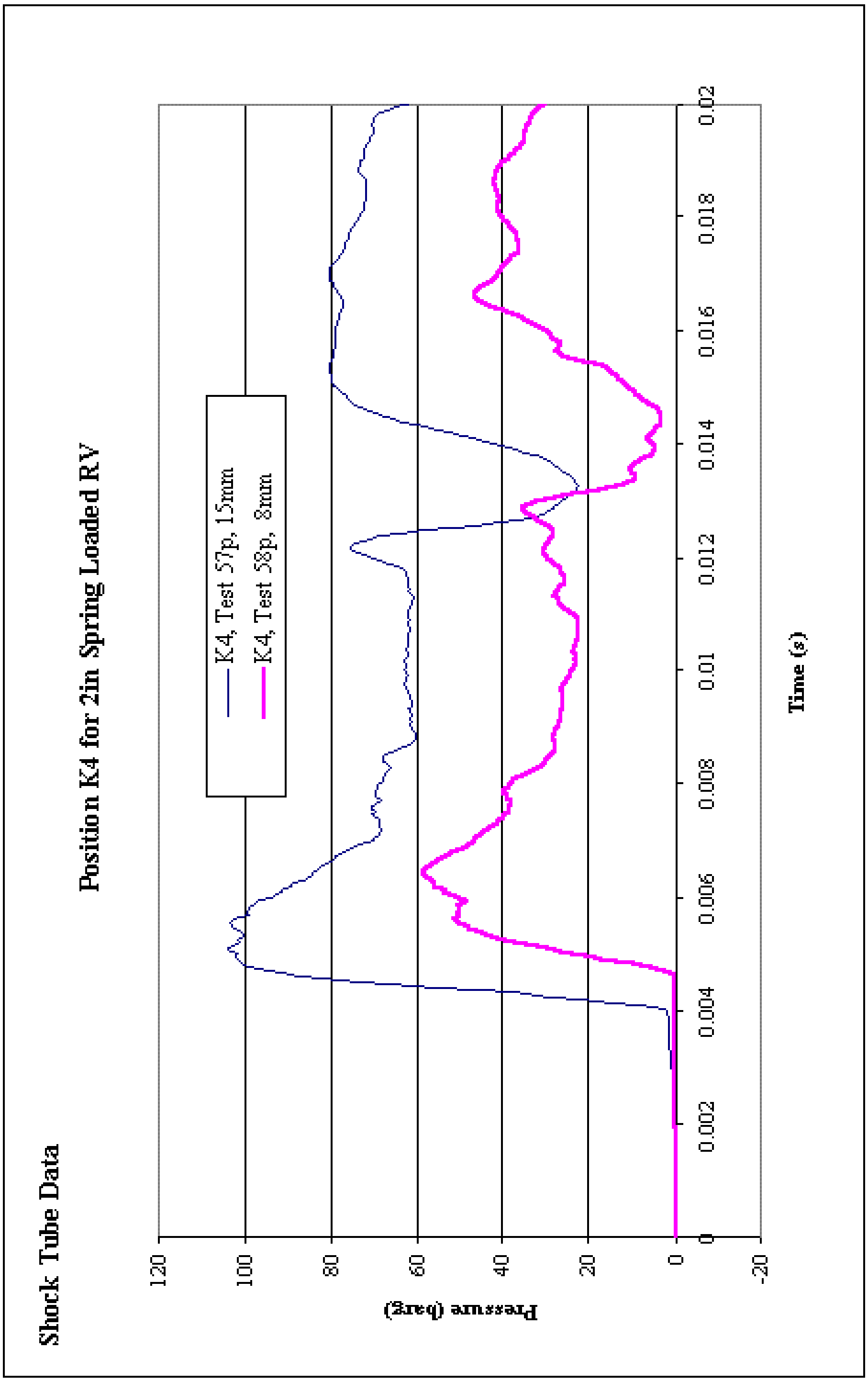

Figure 31 Measured Data - 2H3 SRV at High and Medium Pressure Test

9.4 NEW EXPERIMENTAL TESTS ON SRVS - MEDIUM AND HIGH PRESSURE

The same examination was repeated for the new tests. Firstly the results for the SRVs were compared for the high and medium-pressure test (Figure 34) and the same trend was observed. The amount of time that elapses between the pressure starting to rise and it peaking is longer for the medium-pressure test than the high-pressure one.

This is also supported by the detailed analysis, where Figure 32 and Figure 33 are based on the opening times shown below. In both cases, the correlation is exceptionally high, arguably as high as the correlation for the graphite burst disc in the previous study (Figure 23) and this provide a very high level of confidence in the results.

Table 11 Opening Times for SRV (4L6)

Device	**Test Condition**	**Opening Time (msec)**
Conventional Spring Loaded SRV (4 L 6)	High Pressure	4
	Medium Pressure	5

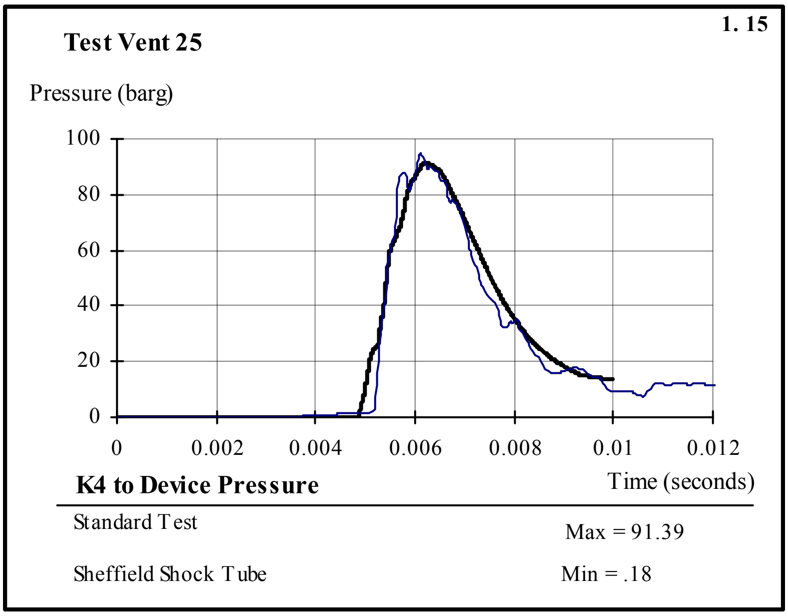

Figure 32 Correlation of 4L6 SRV - High Pressure Test

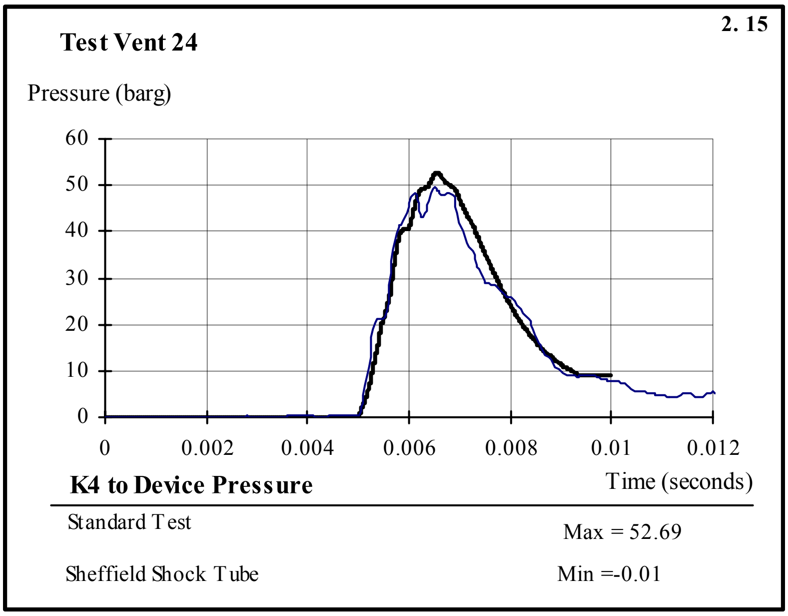

Figure 33 Correlation of 4L6 SRV - Medium Pressure Test

This part of the study confirms one of the findings from the smaller SRV, that the opening time of the valve is pressure related. The valve is 25% slower in the medium-pressure test, compared against the high-pressure one.

However, the results do not support the hypothesis that the fast opening times seen for the small SRV were also a function of its size. The opening times for the larger valve are the same.

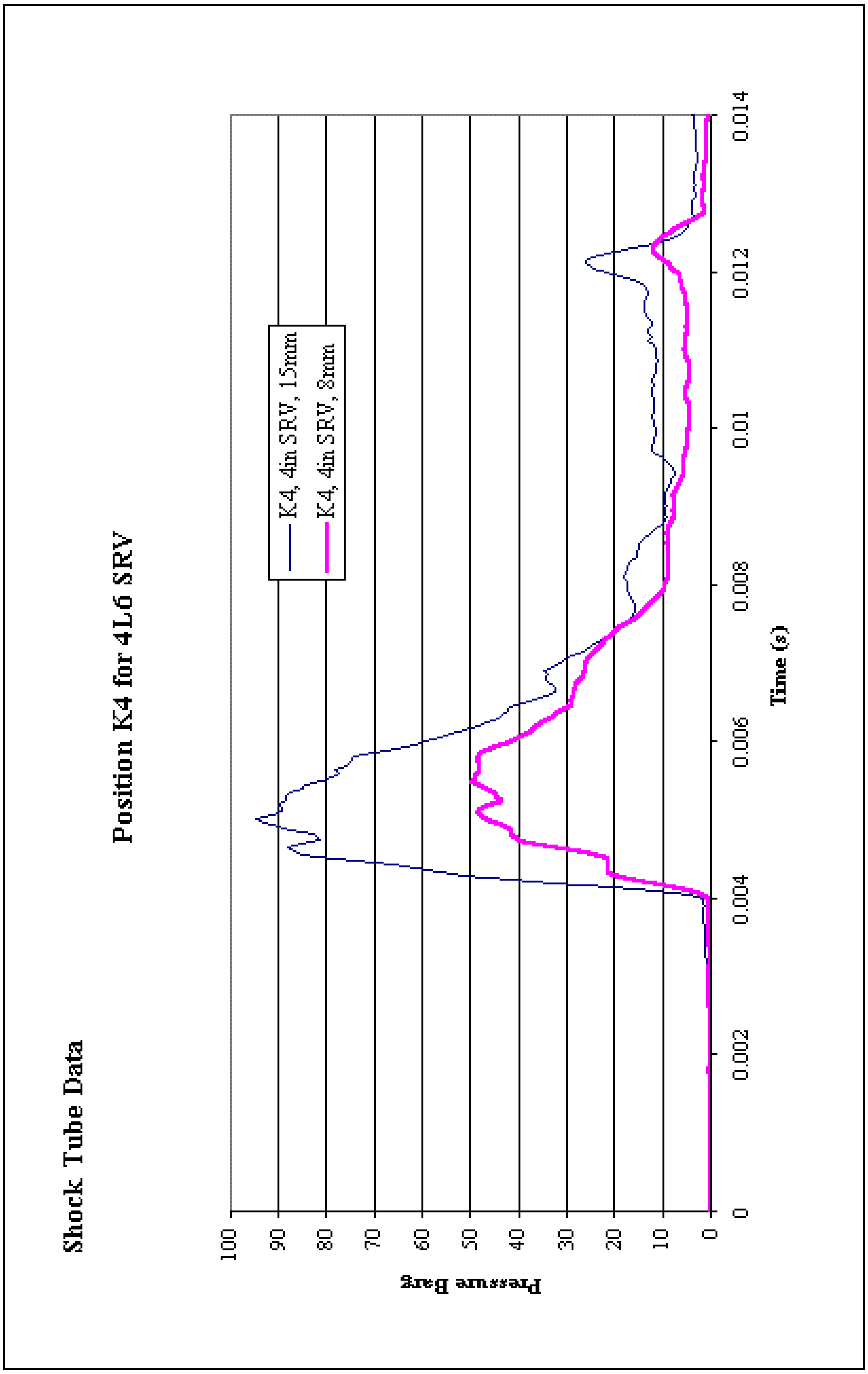

Figure 34 Measured Data - 4L6 SRV at High and Medium-Pressure Test

9.5 NEW EXPERIMENTAL RESULTS - SRVS AT LOW PRESSURE

The measured results for the low-pressure test unusually exhibited some of the 'non-standard' behaviour that was attributed to air in the shock-tube and which was eliminated during the test-procedure in most cases. This meant that the pressure in the tube tended to rise as a series of undulating steps, rather than a steady increase. In turn, it was very difficult to obtain a good correlation when we undertook the detailed analysis, using the simulation model. The best agreement is shown on Figure 35, based on a valve opening time of 10 msec and the agreement is adequate.

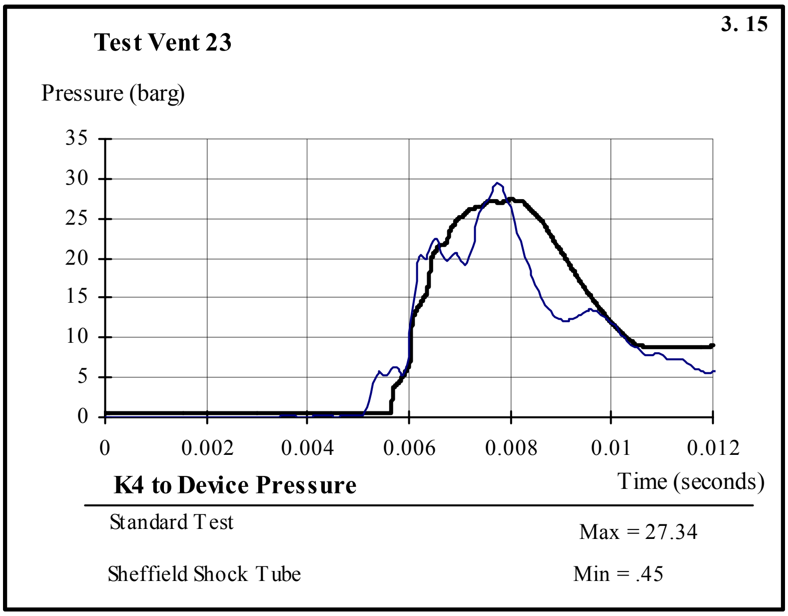

Figure 35 Correlation of 4L6 SRV - Low Pressure Test

The results are summarised on Table 12. This shows the opening times from the three SRV tests together with the typical pressures in the shock-tube; the overpressure is also given (for the set pressure of the SRV of 10 barg):

- Firstly, this confirms that the opening time of the SRV is pressure-related
- Secondly, we have also attempted to estimate the opening time for the case when the valve is subjected to an overpressure of only 10%. And although this is not a reliable finding (because the data set is to small and too widely spaced) we believe that the opening time could be more than two or three times the maximum value predicted so far in this study (10msec)

Table 12 Performance Results for SRV (4L6)

Test Condition	Typical Shock-tube Pressure (barg)	Overpressure (%)	Opening Time (msec)
High Pressure	62	520	4
Medium Pressure	33	230	5
Low Pressure	17	70	10

Our the study showed one further, unexpected finding in the low-pressure tests in that the 4L6 SRV did not exhibit the classic conditions of valve chatter, seen with the 2H3 SRV in the previous tests (Figure 36). However, the reason for this is the difference in the set pressure of the valves.

- The set pressure of the 2H3 SRV was 15.4 barg and hence materially the same as the basic pressure in the shock-tube (15-17 barg)
- The set pressure of the 4L6 SRV was lower, at 10 barg, and hence it was well below the shock-tube pressure.

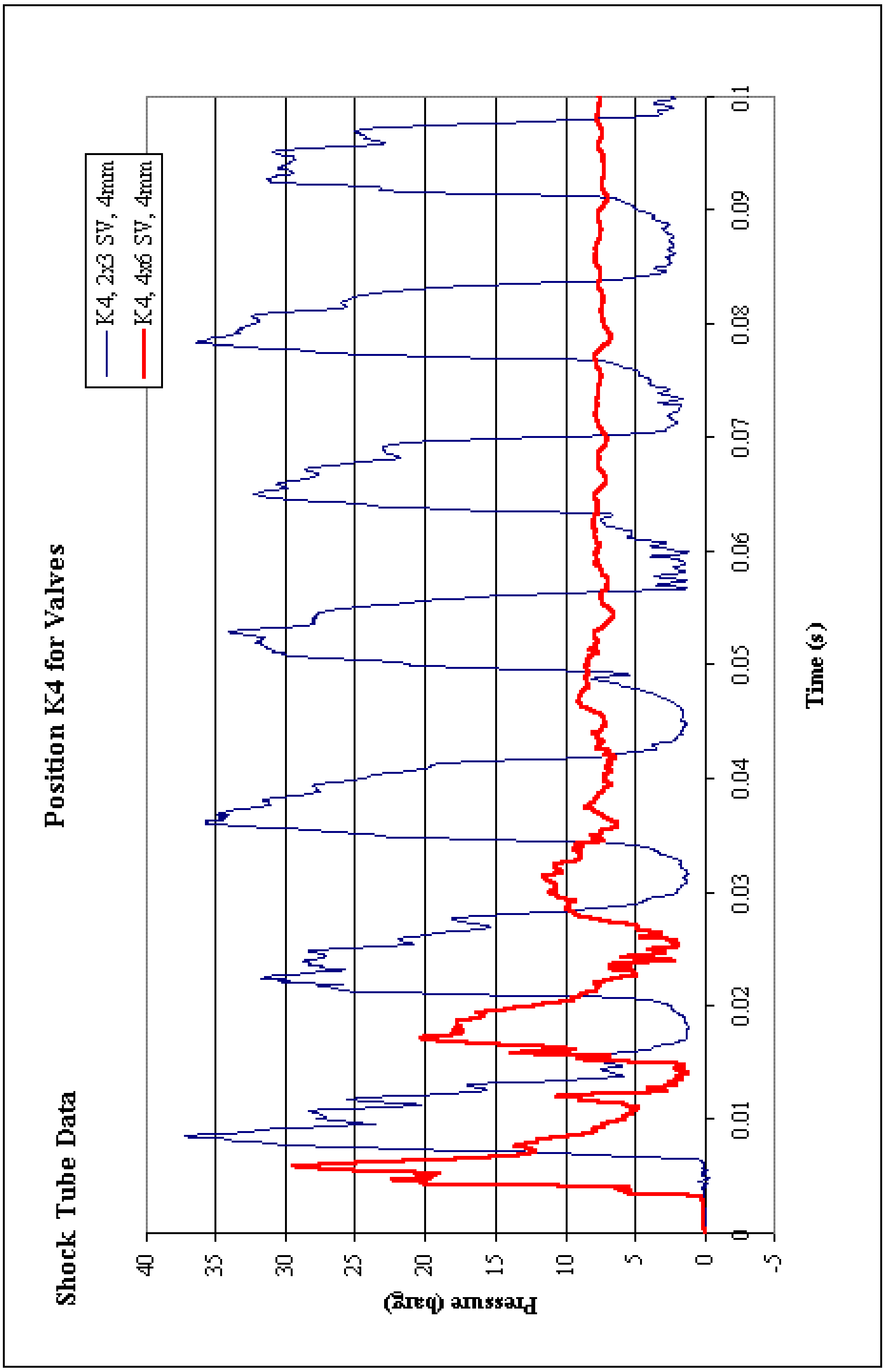

Figure 36 Measured Data - 2H3 and 4L6 SRV at Low Pressure

9.6 NEW EXPERIMENTAL TESTS ON RVS

This study also included a brief examination of relief valves as well as safety valves, thereby increasing the width of understanding on relief devices. Typically, these are low-cost valves, often used for thermal relief applications where high discharge rates are not required.

The results from the RV tests were therefore compared against the SRV and these showed that the RV opened more quickly. A typical result is shown on Figure 37 for the high-pressure test, together with the results of the 4in graphite burst disc from the previous study. This graph can only be used qualitatively because the burst pressure of the graphite disc is 15.4 barg compared with a set pressure of 10 barg for the valves. But to obtain reasonable parity, this figure shows the pressure ratio i.e. the measured pressure divided by the burst pressure for each device.

This graph shows that the opening time of the RV is faster than that of the SRV but slower than the graphite disc. And this trend is maintained for both the medium-pressure and low-pressure tests. But, in part, this finding is not intuitive because the aim of the pop-action is to help the valve to lift the disc quickly. However, we believe that there are two reasons for this finding:

- Firstly, the valves are completely different. Even though their nominal size is the same (i.e. 4in inlet), the RV is a very compact device standing only 395 mm high whereas the SRV is almost twice as big, at 686 mm.
- More importantly, we believe that this result is biased because of the high level of overpressure on the valves in these tests, compared with their design performance at only 10% overpressure. The pop-action is intended to give fast response, compensating for the fact that the normal overpressure is low (only 10%) whereas the overpressure is more than 70%, in even the low-pressure test.

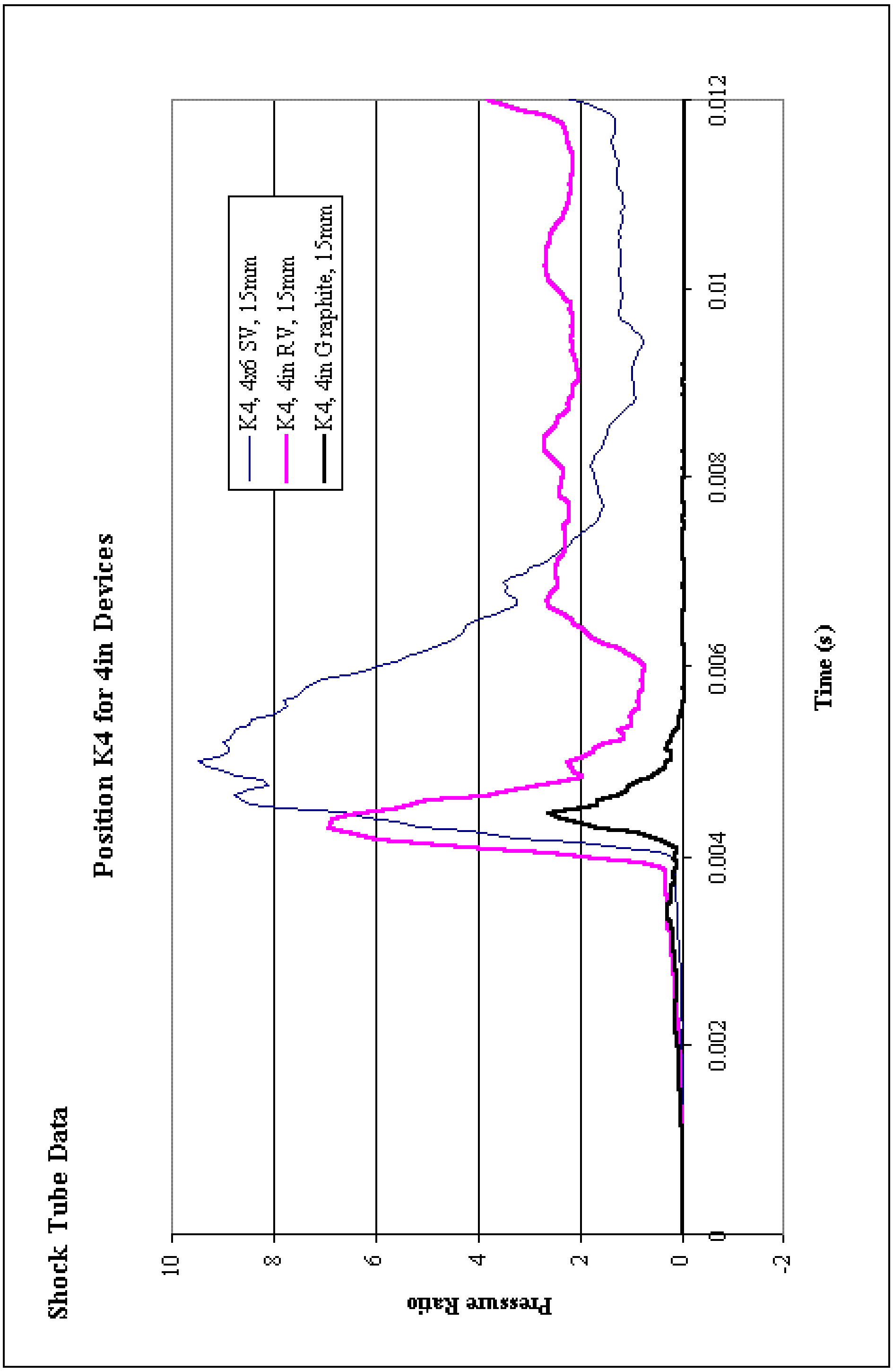

Figure 37 Measured Data - SRV, RV and Graphite Disc at High Pressure

Figure 38 Picture of 4L6 SRV

Figure 39 Picture of 4in RV

9.7 OTHER FINDINGS

The final phase of the study re-examined the results of the bellows SRVs that had been studied in the previous study.

The high-pressure test for the normal spring-loaded SRV is compared with the bellows SRV on Figure 40. This again shows a slight offset that is inevitable in experimental testing but, in all other respects, the performance of the conventional SRV and the bellows[22] version is identical. Similarly, the bellows SRV is subject to the same problems of valve chatter in the low-pressure test, that were fully described and discussed in our previous report.

We therefore conclude that, at least under these test-conditions, the opening time of the conventional and bellows SRVs is the same.

9.8 CONCLUSIONS

One of the main concerns from the previous study was that the predicted opening time for the 2in SRV was of the same order of magnitude as the burst disc, a finding that was completely unexpected. This did not agree with the data given in the IP Guidelines of 80-350 millisec and was faster than the tested value of 25 msec by Kruisbrink, 1990.[23] The SRV data from the previous study was therefore re-examined to determine whether it provided any further information on this issue. In particular we noted that the SRV was small (2H3), it was subjected to a significant overpressure and it was the pop-action type. Subjectively, we expected the opening time to be at the fast end of any performance range and this was confirmed by the initial review. The opening time of the valve was more than 25% slower in the medium-pressure test compared with the high-pressure test. And this means that we immediately established that the fast opening time was biased by the high-level of overpressure on the SRV (over 600%).

The new experimental program reinforced this finding. Very fast response (4 msec) is possible when the overpressure is very high (as would occur in the event of a tube-rupture) but the opening time is significantly slower when the overpressure is low (10msec). We have also attempted to estimate the opening time for the case when the valve is subjected to an overpressure of only 10%, as would be the case in an industrial application. And although this is not a reliable finding (because the data set is to small and too widely spaced) we believe that the opening time could be more than two or three times the maximum value predicted so far in this study (10msec). This is therefore more inline with the findings from the review of the literature sources and from the manufacturers' data which give opening times in the range of 50-100 msec.

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[22] The bellows provide a way of reducing the effect of back pressure on the valve

[23] Modelling of Safety and Relief Valves in Waterhammer Computer Codes, Kruisbrink, A.C.H., Proc. 3rd Int. Conf. Valves and Actuators, BHR Group, STI 1990

Other findings are:

- The study suggests that the size of the SRV may not be a factor. The results are the same for both the 2in and 4in valves
- SRVs may experience valve 'chatter' if over-sized
- The opening time of a bellows SRV is the same as a conventional SRV
- A RV (non-popping) is also capable of very fast response at high overpressure, in fact slightly faster that a SRV. However, this finding is biased by the test-conditions; the pop-action aims to compensate for the effects of low overpressure and so a true test is only obtained under low overpressure conditions

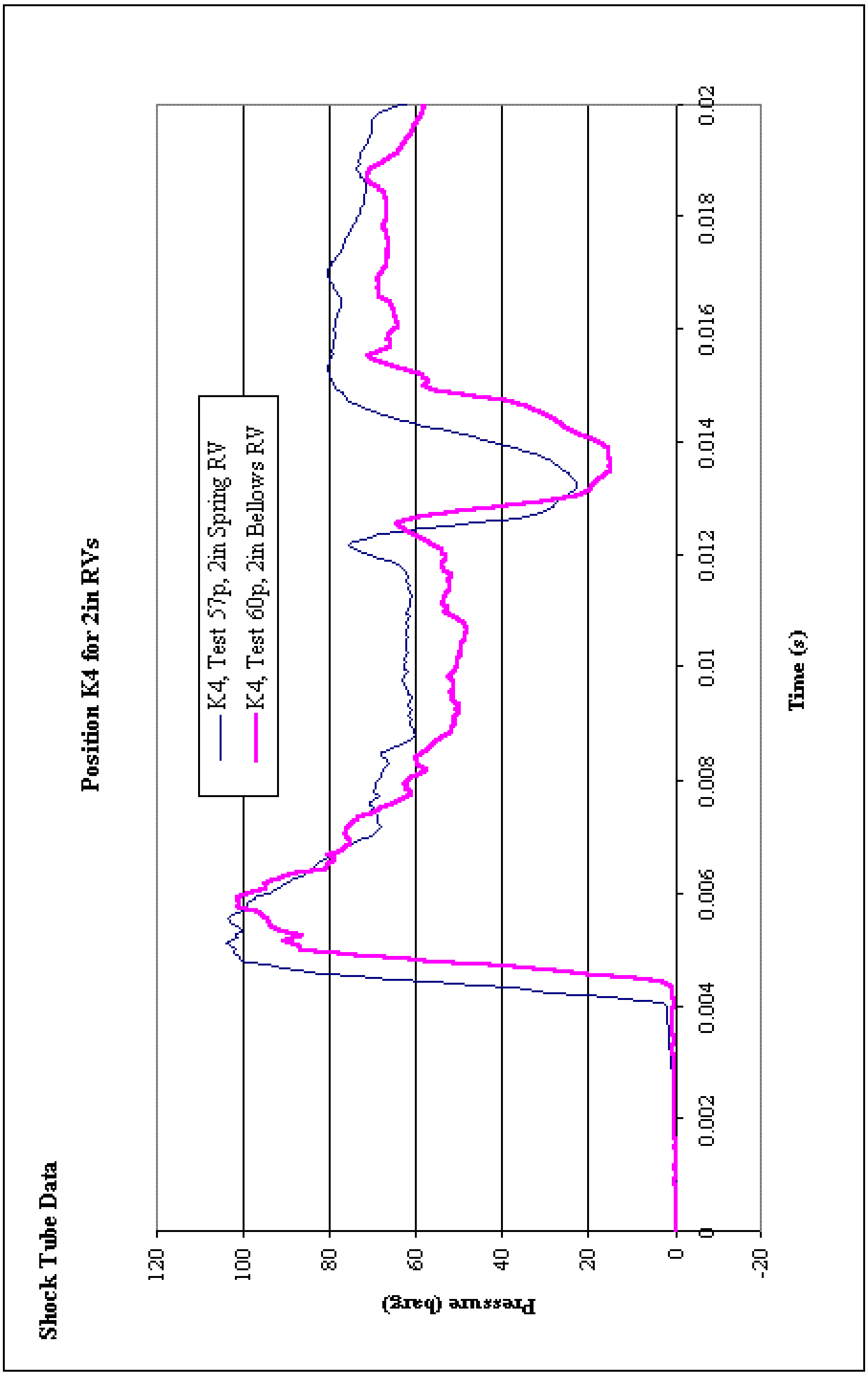

Figure 40 Measured Data - 2in Conventional and Bellows SRVs

10 SUMMARY

10.1 INTRODUCTION

A previous study, undertaken by Sheffield University and PSI, determined the opening times of some relief devices in the context of a high-pressure tube-rupture on a heat exchanger. The study confirmed that fast-acting devices were available but raised several issues that needed to be resolved before industry could use the results. It was essential that the contradictions should be explained and removed to avoid any misuse of the findings from the previous study and to ensure safe use of the relief devices.

To achieve this, the current study was undertaken with three fundamental aims:

- To investigate the apparent anomaly between the response times of the SRV and the burst discs, in that the SRV was almost as fast-acting as a graphite disc (see Section 10.2)
- To obtain better comparison between the performance of the graphite and the steel burst discs (see Section 10.3)
- To determine opening times for SRVs that are more normally used in our industry i.e. industrial sizes (see Section 10.4)

A new programme of testing was therefore undertaken together with a literature survey on existing publications and manufacturers' data. Some of the previous tests were also examined more widely (i.e. tests which were not studied in detail in the previous phase).

One of the key issues of the study was the re-use of an existing test-facility, the one that had been used in the previous study, but this decision proved to be significant. This major change in the underlying target turned out to be a limiting factor:

- The original testing was undertaken as part of a tube-rupture study and the aim was to confirm that fast acting relief devices were available for this application
- This study is targeting wider applications, more consistent with industrial usage of, for example, the offshore oil industry

10.2 RESPONSE TIME ANOMALY: BURST DISCS VERSUS SRVS

One of the main concerns from the previous study was that the predicted opening time for the 2in SRV was of the same order of magnitude as the burst disc, a finding that was completely unexpected. This did not agree with the data given in the IP Guidelines of 80-350 millisec and was even faster than some research papers (e.g. 25 msec). As a consequence, we expressed concerns about the applicability of the findings, in particular whether tests that had targeted the tube-rupture issue could be applied more widely.

This study shows that our concerns were well founded. There is no single opening time for devices; instead their responses are primarily dependent on the level of overpressure and, in part, on their size. This means that the previous findings (i.e. a burst disc rupture time of 1.9 msec and an opening time of 2.5-4 msec for SRVs) are not typical of industrial applications and must not be applied widely across the industry. The very fast response times are only applicable to high overpressure conditions, such as caused by tube-rupture in a heat exchanger.

10.3 PERFORMANCE COMPARISON: GRAPHITE AND STEEL BURST DISCS

This study supports and extends the previous findings for the graphite discs. The rupture time is related to both size and overpressure. But, even at the lowest levels of overpressure that we studied, the disc is still a fast acting relief device. The findings from the film clip, from the tests and from the manufacturers' data all give rupture times of less than 10 msec and are therefore still in line with (and supportive of) the values in the original IP-HSE study.

In contrast, we have been unable to establish reliable rupture-times for the steel discs and hence are unable to compare their performance with the graphite discs. The reason for this is that the amount of deformation that a steel disc experiences before it ruptures is significant in the scale of the test-facility. Under the worst conditions, the 8in steel disc took over 40 msec to rupture but we believe that this is a function of the test conditions and is not representative of the performance in the field.

10.4 INDUSTRIAL APPLICATION

A concern from the previous study was that the 2in SRV was not representative of industrial usage and that the fast opening could be a function of its size. Additionally, there was a big disparity between the capacity of the burst discs and the SRV (i.e. the discs were over-sized and the SRV was under-sized in the context of the shock-tube) making comparative performance unreliable.

A comprehensive review of the test-facility and the sizing of the devices was therefore undertaken (before the test programme began) to try and rationalise the capacity of the facility and the devices, whilst ensuring that the sizes were more typical of industrial use. However, this study shows that we have reached the limits of the existing test-facility. And this is most apparent when reviewing the third aim of this study, that of determining the opening time of devices in industrial application. The constraints of the facility made it impossible to test industrial size devices at their full-flow capacity whilst at only 10% overpressure.

Manufacturers' data and research papers suggest that a rupture time of about 10 msec is suitable for graphite burst discs and about 50-100 msec for SRVs in a normal industrial context. And the results from this study are broadly inline with this data. But given the importance of such information to the industrial community, we cannot recommend that these findings become definitive guidelines. Moreover, the limited amount of information from manufacturers (we contacted 20 SRV manufacturers for data; of these only 8 replied and only 3 were useful) makes definitive, independent guidelines for industrial situations all the more important.

We also have a second area of concern. A simple comparison between the pressure measurements from the previous study and the current one shows good consistency in some cases but errors of up to 18% in others. We do not have enough sets of results to undertake any statistical review; nor can we isolate the reason for these differences. We cannot determine whether there was a significant difference in the pressure/flow conditions generated in the shock-tube or whether the devices are unduly sensitive to a small variation in conditions. Overall, this means that an element of caution must be applied when discussing the findings. In, particular this applies to the SRV testing because the low-pressure tests (the most inaccurate ones) are similar to the pressure conditions that can be experienced in industry.

10.5 CONCLUSIONS

This study was been successful in achieving the first, and arguably the most important of its aims, showing that the rupture/opening times from the previous study are not applicable to normal industrial application and must not be applied through the industry as a whole. The high level of correlation between the measured results and those predicted by the simulation model must also improve levels of confidence in the study and its findings.

The other two aims are less successful, primarily because we have reached the limits of the existing test-facility. Significantly, we are unable to provide definitive information that has the most use in the industry (i.e. the response time of devices at 10% overpressure). We therefore recommend that this current study is seen as both essential and informative, but only as part of an on-going examination that needs more work.

11 FURTHER WORK

This study has addressed some of the outstanding issues from the previous study and applied the findings towards more general industrial application. However, only one of its major aims has been satisfied and a consideration of the repeatability and consistency of the findings has cast some doubt. The amount of information available for industrial applications conditions is still limited and yet we believe that this must be the desired target, to provide well-founded guidelines for the industry.

For these reasons, and because of the paucity of accurate information currently available from manufacturers, we believe that there is still a need for further testing, particularly aiming at the industrial usage of relief devices.

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