INVESTIGATION INTO THE USE OF ACTIVE DETONATION ARRESTERS FOR SOLVENT AND WASTE GAS RECOVERY PROCESSES

S.P.Cooper, Dr.P.E.Moore Kidde Graviner Ltd, Slough: Dr.B.Capp U.K.Health and Safety Executive Explosion and Flame Laboratory, Buxton: Dr.J.Senecal Fenwal Combustion Research Centre, USA.

Environmental demands for greater pollution control can often cause problems for process designers especially where containment and transportation of combustible materials are concerned. The authors present one of the most recent developments in explosion protection, where active systems are investigated as a means of blast mitigation of pipe line explosions.

Keywords

PIPELINES, DEFLAGRATION, DETONATION, SUPPRESSION, CONTAINMENT, ISOLATION.

Introduction

The current trends of collecting waste and toxic gases for disposal, have introduced systems for gas recovery which can be both complex and hazardous in normal operation. Processes which emit gas as a by product or as a consequence of large scale material movement, can have fume extraction systems installed. These are often connected to incineration packages, used to dispose of the harmful products.

These gas recovery systems usually consist of pipe used to connect the process to the collection and disposal device. The pipes are usually of large bore and can often be many hundreds of metres in length. In addition to this, the pipes may have multiple points of extraction linking into a common pipe to the disposal device. This presents the prospect of communicating an explosion to many parts of a process in the event that combustion occurs in any part of the pipe or at a specific location.

If the combustion event is allowed to propagate unrestricted along a pipe it is possible to create the conditions of detonation [1]. The consequences of detonation within such a system are considerable as the flame, pressure and shock wave loading generated during detonation, can cause mechanical damage to the process, and environmental damage when released in an uncontrolled manner into the surrounding area.

This paper sets out to describe the ways of mitigating the effects of such an event using active detonation barriers by detailing the results of research work undertaken recently into active systems for suppressing and isolating detonations.

Hazard Assessment

Combustion of hydrocarbon vapours in pipelines can occur when the concentration of the vapour and air exceed the lower explosible limit. The nature of the event will be dictated by the fuel/air mixture, the fuel type and the geometry and processing conditions of the pipe.

Depending on the intensity of the event, the combustion wave may propagate along the pipe at a few metres per second up to a few hundreds of metres per second. These deflagration events may be dealt with by flame arresting systems and will normally generate low pressures within the confinement of the pipe system. However it is possible for the explosion to develop to a detonation for fuel/air mixtures with near stoichiometric composition, e.g. between 2.0 and 6.1% for n-butane. The nature of such an explosion is that very high flame speeds are generated, typically 2000 Km/s, with a corresponding peak pressure typically 30-50 barg. Table 1 shows typical values of detonation velocity for various hydrocarbon gases with stoichiometric compositions.

The aim of the research work was to investigate the potential use of suppression, rapid acting valves and explosion vents separately, and as combination packages, as means of mitigating the effects of deflagrations and detonations in small and large bore pipe.

The tests were undertaken at the UK Health and Safety Executive Explosion and Flame Laboratory in Buxton as a part of the American Petroleum Institute initiative (450mm diameter pipe) and at the Combustion Research Centre of Fenwal Safety Systems Inc, Marlborough, Massachusetts (150mm diameter pipe).

Description of Protection Concepts

It is often impracticable to totally eliminate all sources of ignition and/or remove or deplete the concentrations of oxygen or fuel. Therefore, it is often the case that recovery systems are designed with the prospect of ignition in mind. The options available for blast mitigation are:-

Containment

Construct the entire process in a way as to contain the explosion event by ensuring that the entire process can withstand the maximum explosion pressure/detonation (Pmax) without rupture.

Deflagration Protection

Arrest the propagation of flame whilst in its incipient stages.

At the deflagration stage the flame speed is moving at speeds <600 m/s (typically) and the pressure shock is low at 10 - 15 barg (typically). By installing protective devices or systems, the flame can be arrested or quenched, limiting the explosion pressure to values well within the pressure shock resistance of the process. The overriding criteria for a suitable arrester is that, firstly, it is capable of quenching or arresting flame and secondly that it is installed in such a way that the flame is not allowed to travel the required distance to reach detonation velocity.

The options available for use in this area are:-

Passive Flame Arresters

Wound crimped steel ribbon devices installed in the pipe line quenching the flame by removing the heat as the gas passes through the numerous narrow channels. They may be installed either side of an identified potential ignition source. In reality they present a restriction to the pressure and flow characteristics of the pipe, especially if the arresting element can become blocked with solids entrained on the air flow.

Explosion Venting

Installation of weak membranes into components or pipelines to relieve the explosion pressure and flame, in a controlled manner, to atmosphere. The vents should be placed at intervals less than the predicted run up distance to detonation and should be equal to or greater than the cross sectional area of the pipe. In normal operation the discharge of flame and pressure from the pipe can be considerable, therefore great care must be exercised as to the location of the vent and the direction at which the flame will be released. Explosion vents will reduce the effects of accumulated pressure within the pipe but are unlikely to prevent flame continuing past the vent.

Explosion Suppression [2]

Detection and extinguishment of the flame in its incipient stages by rapid injection of a chemical suppressant into the flame. The distance between detectors and suppressors must be less than the run up distance to detonation. The suppressant selected must have been proven to be successful in extinguishing the predicted explosion event. Unlike venting, explosion suppression will arrest the propagation of flame and can be placed around perceived ignition sources or along the entire length of the pipe.

Explosion Isolation

Activation of a mechanical valve or chemical barrier to arrest the propagation of flame in a pipe. Valves or chemical barriers would be effective when located around potential ignition sources and present no restriction to the flow characteristics of the pipe in normal operation.

Detonation Protection

Although deflagration protection of pipelines can provide adequate explosion safety, in practical circumstances where pipe lengths are significant, the deployment of these techniques can be expensive. The alternative is to consider effective detonation protection measures.

The requirement for effective detonation protection is to arrest the propagation of a detonation limiting the potentially destructive force of the pressure shock waves.

To build an entire process capable of withstanding pressure shock in excess of 50 barg can be impracticable. It is therefore advisable to concentrate on the options of either deflagration protection or detonation protection or, where necessary, a combination of both.

Whilst it is prudent to prevent ignition from occurring and failing that, to minimise the consequences of an ignition by deflagration protection, conditions can prevail where an explosion can be initiated from a vessel offering none of the protection potential previously described.

In the recovery of waste gases from a bulk oil, petroleum ship or process vessel, it is possible to create an ignition which can be allowed to travel a great distance. For this scenario detonation protection devices and systems should be considered to prevent destruction of the vapour recovery system or, indeed the vessel, should ignition onshore travel along the pipe unabated.

The options that exist for this type of protection are:-

Passive Detonation Arresters

Passive devices for arresting detonations are similar to those described under the category of passive flame arresters but with the additional ability to decouple the shock wave and withstand the large axial forces (shock waves >50 barg). These devices also have the drawback of presenting an in line restriction, coupled with potentially filtering out entrained solids and therefore becoming blocked after a period of time.

Active Detonation Arresters [4]

These are systems that detect the propagating flame front and activate rapid action valves and suppressors to prevent the propagation of flame beyond the arrester barrier. Suppressors and valves are located in strategic positions and supplemented with vents (where necessary).

Application of Active Detonation Arresters

Although not a new device or system, the application of suppression, valves and vents for the mitigation of detonation events is a new explosion protection concept.

Active isolation stations are located in the pipe at strategic positions (figure 1). Typical areas that would be considered would be the vessel to pipe interface; the incinerator to pipe interface; branches from the pipe to other extraction stations. The isolation barriers are activated by explosion detectors installed upstream of the barrier. A signal is sent to a control unit which, in turn, sends signals to the isolation device(s) actuators to operate (figure 2).

Explosion suppressors may be used to establish a high concentration of chemical extinguishant at the barrier. On entry into the chemical barrier, the flame would be extinguished, arresting the combustion process. The pressure formed as a consequence of combustion, would be allowed to dissipate harmlessly throughout the pipe or out of a convenient pressure relief vent or contained at the barrier by activation of a rapid action gate valve. The suppressors are required to activate in 10-20 milliseconds and must introduce a chemical agent capable of extracting the high flame energy.

Rapid action valves close in 20-40 milliseconds (typical) presenting a robust steel plate to the oncoming shock wave. Although the valves are designed to withstand high pressure loads, impact loads of the magnitude anticipated from a terminal velocity detonation, would result in the deformation of the valve plate with necessary replacement resulting. It is therefore, preferable to locate a suppressor to reduce the pressure or install a pressure relief device in the line ahead of the valve.

Description of 450mm Pipe Test Work

The tests were undertaken at the Buxton Laboratory of the Health and Safety Executive. The tests were performed in a pipe system constructed under contract from the American Petroleum Institute (API) for the specific task of testing Detonation Arresters to the United States Coast Guard (USCG) test Protocol.

The pipe was heavy schedule, carbon steel comprising 3 metre to 14 metre lengths joined by flanges rated to 600lbf (ANSI). The approximate length available for testing was 147 metres (figure 3). In addition to this, two 600/150lbf (ANSI) adaptor pieces were made available and a long sweep tee with 150lbf (ANSI) flanges. The pipe configuration for the initial test run is shown in figure 9 as an example.

Connections were made in the outer wall of the pipe to accept the installation of explosion pressure detectors. Entries and connections were supplied in the tee for installation of explosion suppressors. At strategic locations on the pipe, tappings were provided for the installation of optical flame sensors. The pipe was suspended above ground on wooden supports and anchored at the discharge end with concrete blocks. A platform was erected at the location of the valve to facilitate essential servicing during the tests.

In addition to the instrumentation facilities provided by the HSE, video cameras were positioned at the pipe ends during all of the tests. Additional high speed photography was provided by the HSE Film Unit.

Instrumentation

Optical flame detectors were to be employed to measure flame speeds at critical points along the pipe. Pressure transducers were also deployed to measure the peak pressures at the valve and vent ports.

Pipe Control

The pipe was filled with stoichiometric propane/air at a concentration of 4.1% by volume in air. Cylinders containing 95% pure Propane were used to deliver the gas through a calibrated flow meter and regulator set. The gas concentration was measured by an Infra-Red Gas Analyser. The explosions were initiated using an electrically heated wire coil at the closed end of the pipe.

Detection

Explosion Pressure Detectors were used exclusively throughout the test program. The detector was fitted with an 0.2mm (0.008 inch) thick diaphragm. The detection position did not alter nor did the pressure threshold setting of 0.1 barg. The detector was directly connected to an Explosion Protection Unit (EPU) which was located in the control room. The EPU contained the system monitoring function and the capacitor discharge circuitry used to activate the initiators on the rapid action valve and suppressors. These two devices were used to detect the presence of an explosion and to activate the protection devices in each test.

Explosion Suppressors

These devices comprised self contained canisters filled with suppressant and pressurized to 60 barg. They were activated explosively using a combination of No.6 star Detonator and Line

Cutting Charge. The canisters were directly mounted on to stub pipes which were themselves, welded to the pipe (see figure 4). On activation a diaphragm, sealing the canisters, was explosively opened allowing the suppressant to discharge through an unrestricted 76mm diameter orifice directly into the pipe. The time from initiation to effective discharge was 10-15 milliseconds. The number of canisters and the type of suppressant used differed in the program in order to establish the efficiency of the system.

Suppressant

The suppressant used in the trials was a sodium bicarbonate based formulation and water.

Rapid Action Valve

The valve was rated for installation within 150lbf (ANSI) flanges and was supplied in the standard 10 barg pressure shock configuration (figure 5). The valve closing time depends on the actuator used to drive the valve piston down onto its seat. The actuator comprised canisters of pressurized, dry nitrogen. Each canister was opened by a high pressure gas generator (cartridge unit) which was activated by the explosion protection unit, described earlier. The canister pressure and number of canisters were varied during the tests to increase the efficiency of the valve by reducing its closing time. The canister outlet port was connected to the valve cylinder piston actuator through a high pressure hose (3/4 inch nominal bore).

Test Programme

The test results that follow are divided into two groups - Phase 1: visual and Phase 2: instrumented. During the visual trials, video cameras and high speed film was employed to undertake the proving of the various concepts and to allow modifications to take place prior to a fully instrumented test.

Configuration for Test Program

For this series of proving trials it was determined that, to enable the rapid action valve to close in time, the full length of the available pipe (147 metres) would be required. At detonation velocity (approximately 2000 m/s) this would give the valve approximately 50 milliseconds to close assuming that the pressure detectors do not see the event until such time as the explosion reaches the over driven detonation state (about 51m from the ignition point at the closed end).

The valve was to be located at 90 degrees to the main pipe run and situated approximately 3.5m away from the centre line of the main pipe run. A long radius branch tee was employed to represent a typical on site condition where long sweeps are preferred to reduce pressure drops in long pipes. It was accepted that this would encourage the explosion/detonation to turn the corner.

A vent panel constructed from aluminium sheet was located at the end of the main pipe run. This sheet had a calibrated burst pressure of 7 psi g (0.47 barg). A stoichiometric propane/air mixture was present throughout the entire pipe prior to ignition.

Phase 1 Visual Results.

First Test

This test, with a pipe flame speed measurement, was designed only to register the effects of venting a detonation (all previous explosions had been run into a passive detonation arrester). The test recorded a flame speed datum of approximately 1800 m/s. The pipe successfully vented the event with no damage evident.

Second Test

This test had the valve located in the standard configuration with an explosion detector located 51 metres from ignition. The object of the test was to vent a detonation along the main pipe run and to prevent propagation of flame along the branch by rapidly closing the valve. The valve was fitted with one actuation canister (4.4 litre pressurized to 40 barg) and connected to the valve by a single high pressure hose.

The system detected the detonation at the over-driven stage and the valve closed off, sealing the pipe branch and preventing flame propagation along the branch. No flame or pressure passed through the valve. The detonation was successfully vented out of the main run vent.

Third Test

Test three was a confirmation test for the valve in the same configuration and with the same operating parameters as in test two. The angle of viewing was changed in this test with the cameras placed viewing down the branch. A sheet of plexi-glass was placed on the branch pipe end and secured in place with wooden batons. This provided both a seal for pipe (to prevent gas leakage) and provided a suitable viewing port for cameras.

Shortly after detection, it was observed that the valve operated (cartridge unit fires above valve flange to give visual signal), and as the valve closed the flame could be seen to appear at the branch (approximately 35 milliseconds from detection). It was apparent that although the valve worked successfully in this test, with no flame or pressure

breakthrough, the margin of time available for successful closure is very short (<50 milliseconds).

Fourth Test

Test four was a repeat of tests two and three. It should be noted that the valve had not been recommissioned in any way other than to replenish the actuation canister. The valve blade and seal were the original units supplied.

Approximately 50 milliseconds after detection, the valve closed and the plexi-glass burst open allowing an energetic fireball to be released. Flame had passed around the plate and had ignited the fuel air mixture present in the void between the valve plate and the plexi-glass.

The reason for the failure was quite apparent on inspection. The valve plate had become deformed and bowed by 10mm at its centre, and as a result, had not seated properly. In the bore of the valve is a blade support lobe cast into the valve body. This lobe provides reinforcement for the blade once it is seated. When the valve was actuated, the blade, instead of gliding into its seat, rammed into the lobe thus allowing a gap of approximately 20mm through which the flame was allowed to pass.

The conclusions drawn from this failure were that the two previous tests (where no plate inspection had taken place) had rendered permanent deformation to the plate to the point where the plate leading edge no longer located in the seating position. This was confirmed by the experience that, after the activation of the valve in test two, the valve was difficult to open and a shear pin, holding the valve cylinder to the body, snapped whilst the blade was being drawn up into its set position. At the time, this was thought to be accidental but, after the failure, this suggested that permanent valve blade deformation had occurred during the previous tests. The valve was repaired and put back into commission (figure 6).

Fifth Test

Following the failure in test four, it was decided to increase the margin of safety by attempting to reduce the valve closing time. The standard arrangement for the valve (specified by the manufacturer) was to install a 4.4 litre canister pressurized to 40 barg. It was calculated that the valve cylinder volume was marginally in excess of 5 litres therefore a significant fall in actuation pressure occurred during the valve operation.

The test undertaken used two canisters (figure 5) of the same dimensions and pressure, discharging through a 'Y' piece and into the cylinder.

The closing time was reduced from a consistent 50 milliseconds with one canister (measured during tests 2 and 3) to 23 milliseconds with two. It was decided that all future tests with the valve would be conducted with two canisters.

Sixth Test

The last test in the proving trials was to determine the effectiveness of a suppression system. The detection and activation system remained the same but the valve was disconnected and replaced with suppressors. The two suppressors were located on the tee before and after the branch. Each suppressor contained 16kg of powder suppressant and was pressurized to 60 barg. The main pipe end was sealed with an aluminium sheet in the normal way and the branch end sealed with plastic.

It could be clearly seen that the aluminium vent bulged some 10 milliseconds after detection. This was concluded to be due to the action of the suppressors located nearby as they discharged their pressurized contents. The detonation arrived at the pipe run and branch end simultaneously but instead of the loud report associated previously with the detonation, the event was substantially muffled and there was no evidence of flame passage out of either the main pipe run or out of the branch (figure 7).

As the powder barrier was clearly being established as early as 10 milliseconds after detection, long before the detonation flame front arrived, it would appear that such a barrier, formed of a high concentration chemical powder suspension in air, was contributing to the mitigation of the effects of the detonation wave.

Phase 2 Instrumented Tests.

The summary of trials in the instrumented phase (2) is shown in figure 8.

Trials 1 - 8 were flame speed trials conducted to calibrate the pipe instrumentation and fuel delivery systems. Flame speeds of approximately 1800 m/s were recorded in the main run of the pipe.

Tests 1 - 3 have the barrier pressure recorder located 3.5m away from the main pipe run. In this configuration higher pressures were recorded than in tests 6 - 8 where the barrier was moved to within 1.5m of the main pipe run and the tee sweep reversed (figure 9).

Test 9 was conducted with a rapid action valve located at the barrier position and activated by the detection system in the main pipe run. Pressures consistent with those in the main pipe were recorded as the branch was closed off by the valve.

Test 13 employed 2 - suppressors each containing 16kg of powder suppressant located at the tee, either side of the branch. Significantly lower pressures in both pipe and at the barrier were recorded. The branch was allowed to vent freely.

Test 16 was a repeat of test 13.

Test 17 was a repeat of test 13.

Test 18 employed 2 - suppressors each containing 12 litres of water located at the tee, either side of the branch. Higher pressures were recorded in the main pipe than with the powder suppressant but similar levels at the barrier. The branch was allowed to vent freely.

Test 19 was a repeat of test 18.

Test 20 was a repeat of test 18.

Test 23 was a repeat of test 13 but with a rapid action valve activated in the branch at the same time as the suppression system. Higher pressures were recorded in both the main pipe and branch due to the branch being closed by the action of the valve. The barrier pressure was however, significantly lower than when the valve was deployed on its own.

Comparison of 450mm Trials with 150mm Trials in USA

Following completion of the tests at Buxton, further work was carried out in pipes of 50mm and 150mm [3]. A comparison between the 150mm and 450mm trials is possible for suppression efficacy.

Figure 10 clearly shows the reduction in pressure that can be obtained by the introduction of suppressant ahead of the advancing flame. The pressures recorded are consistent with those measured in the 450mm pipe. Further work confirmed that the barrier becomes more efficient with a greater concentration of suppressant (figure 11).

Detection of the event is critical to the timely introduction of suppressant or closure of a valve. To this end, the geometry of the pipe system plays a important part in the detection selection and location criteria. Figure 12 shows the effect that a single 90° bend has on flame velocity compared with an explosion in a straight pipe of the same length.

From figure 13 it is evident that, at the early stages of combustion (when the event is a deflagration) it is advantageous to detect the ensuing pressure wave. If however, due to process conditions, it is not permissible to employ pressure as the detection medium, the delay in sensing the event using flame sensors may influence the distance between the detector location and the relative position of the barrier.

Conclusion

The active detonation arresting system has measurable benefits over conventional passive devices and the research work described above confirms the proof of concept. The tests demonstrated that suppression and rapid action valves alone, can arrest detonations in pipelines. Combined, the two means of isolation provide effective reduction in pipe line pressures coupled with mechanical isolation to prevent transmission of blast waves and further ignition events.

Additional work is being undertaken on pipes of 600mm diameter to validate future system designs.

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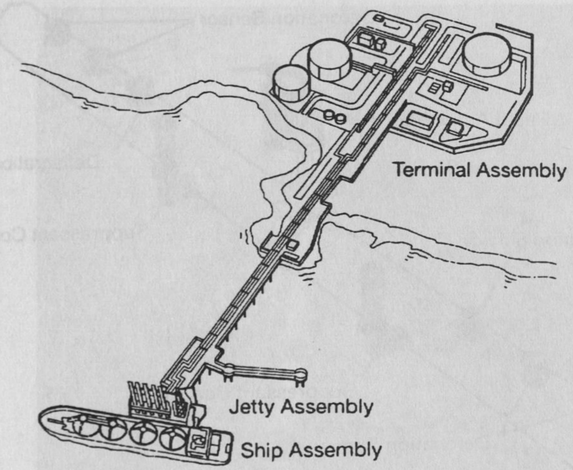
DETONATION PARAMETERS FOR FUEL-AIR MIXTURES

Fuel	%Fuel by Volume	Velocity (m/s)
Acetylene	7.75	1864
Hydrogen	29.6	1968
Ethylene	6.54	1822
Ethane	5.66	1825
Propylene	4.46	1809
Propane	4.03	1978
n-Butane	3.13	1796
Methane	9.48	1801
Hydrogen Sulphide	12.3	1647
n-Hexane	Aerosol	1795

TABLE 1



Ship to shore off-loading system

Figure 1

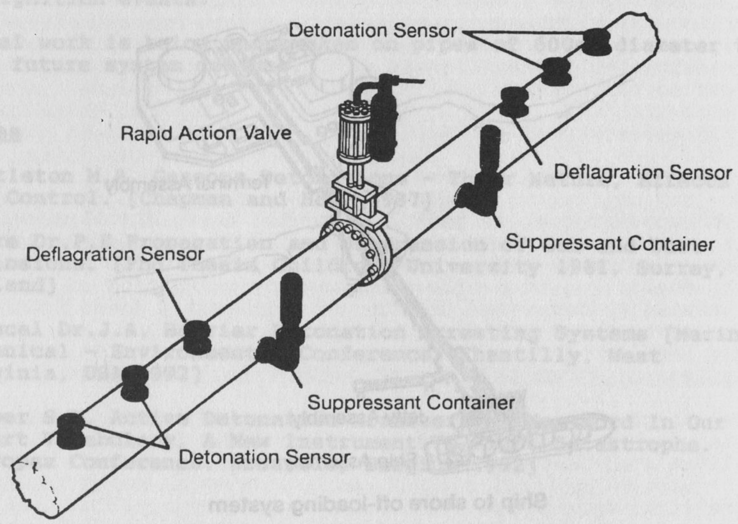


Figure 2

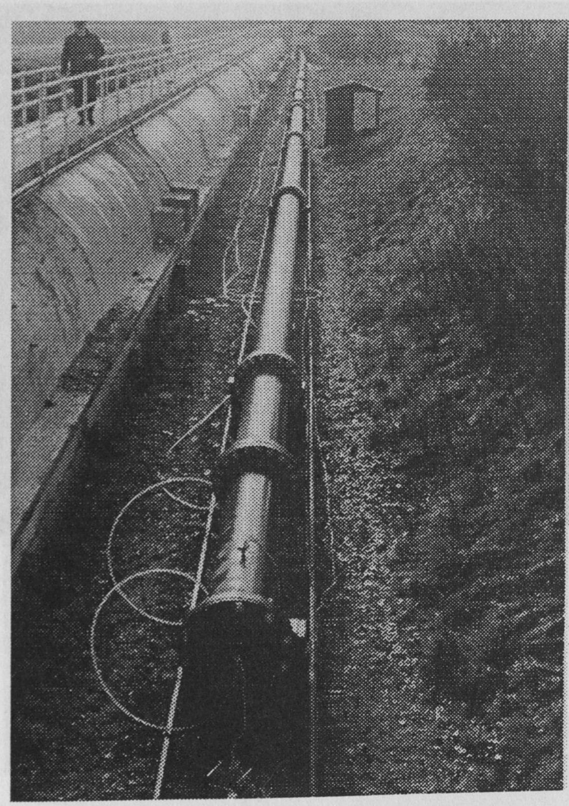


Figure 3

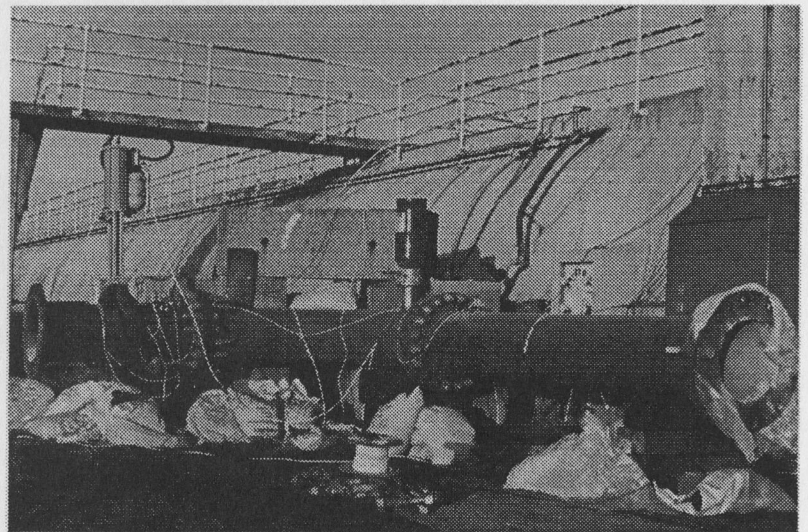


Figure 4

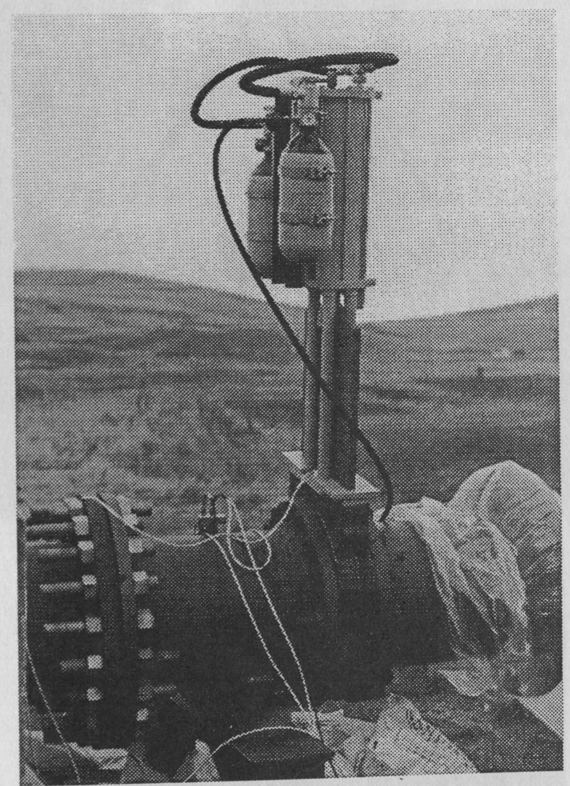


Figure 5

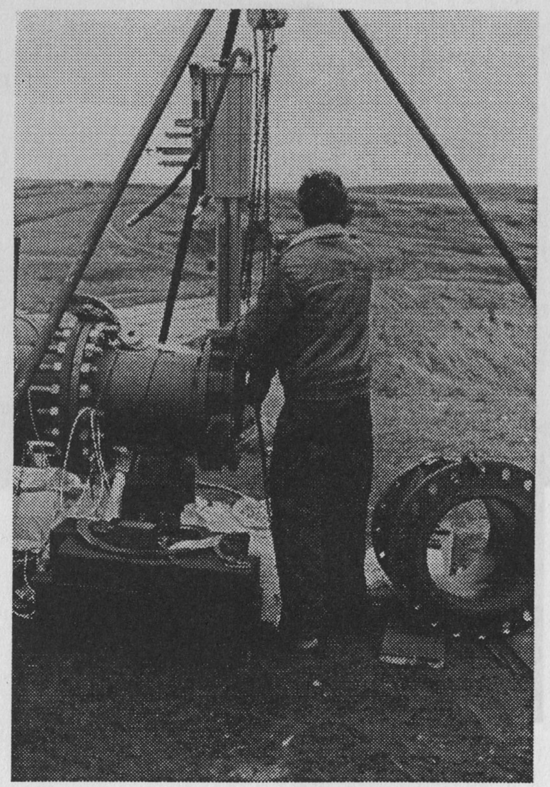


Figure 6

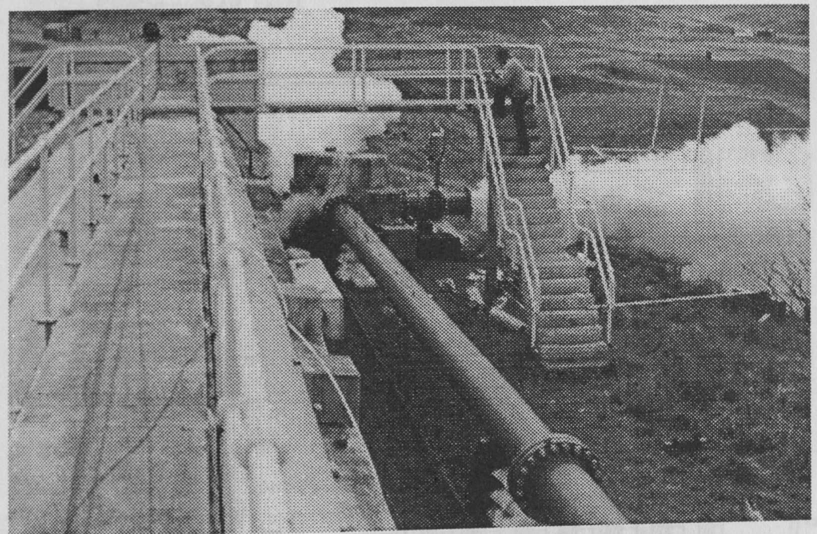


Figure 7

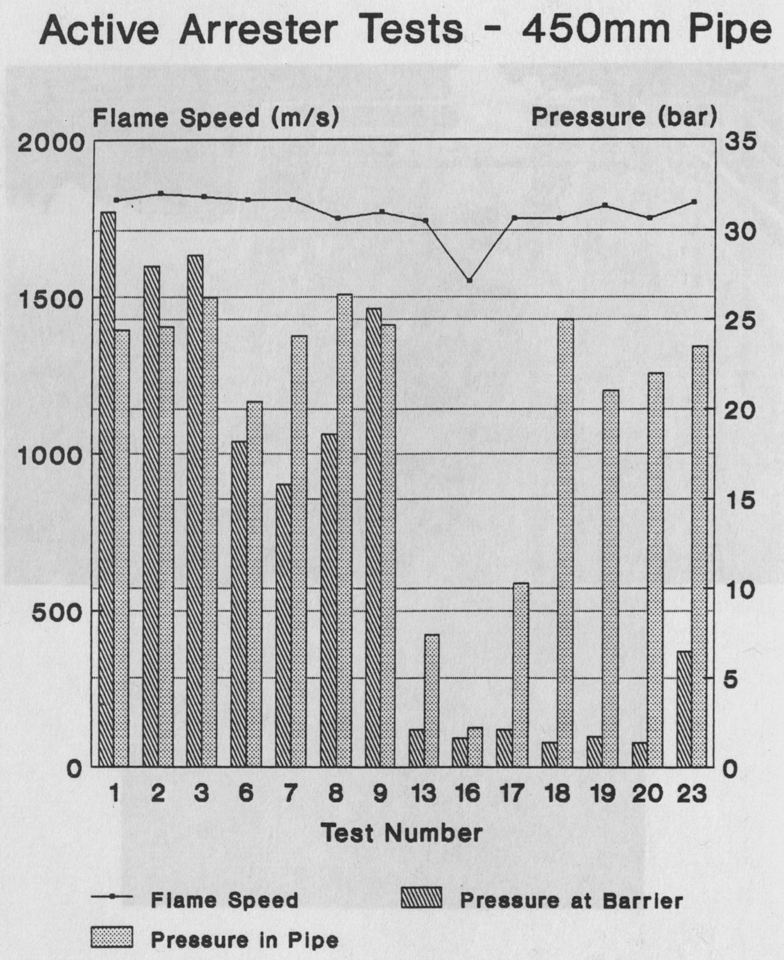


Figure 8

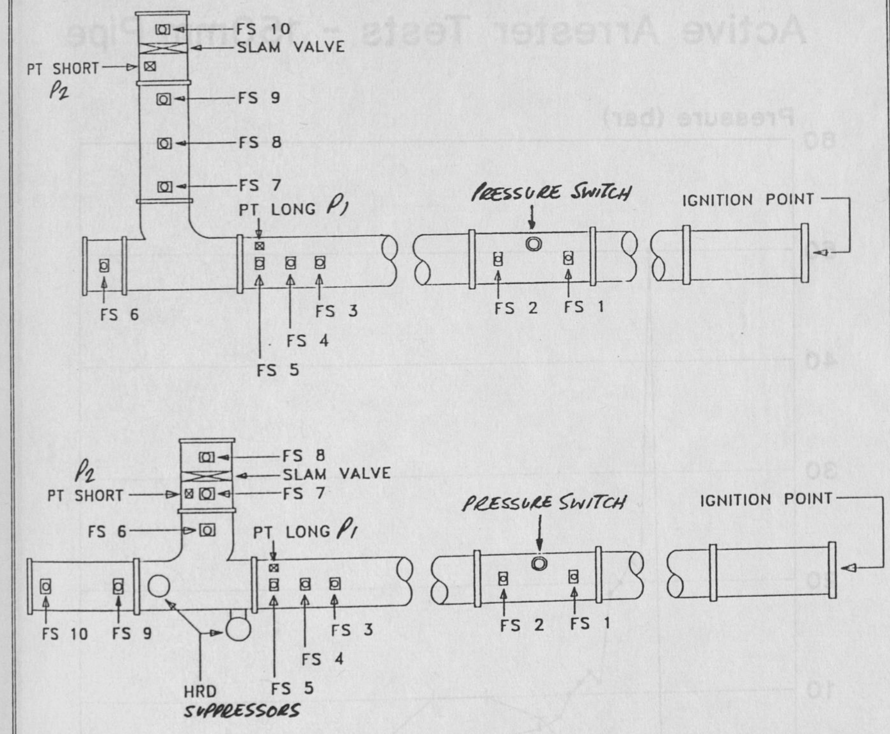


Figure 9

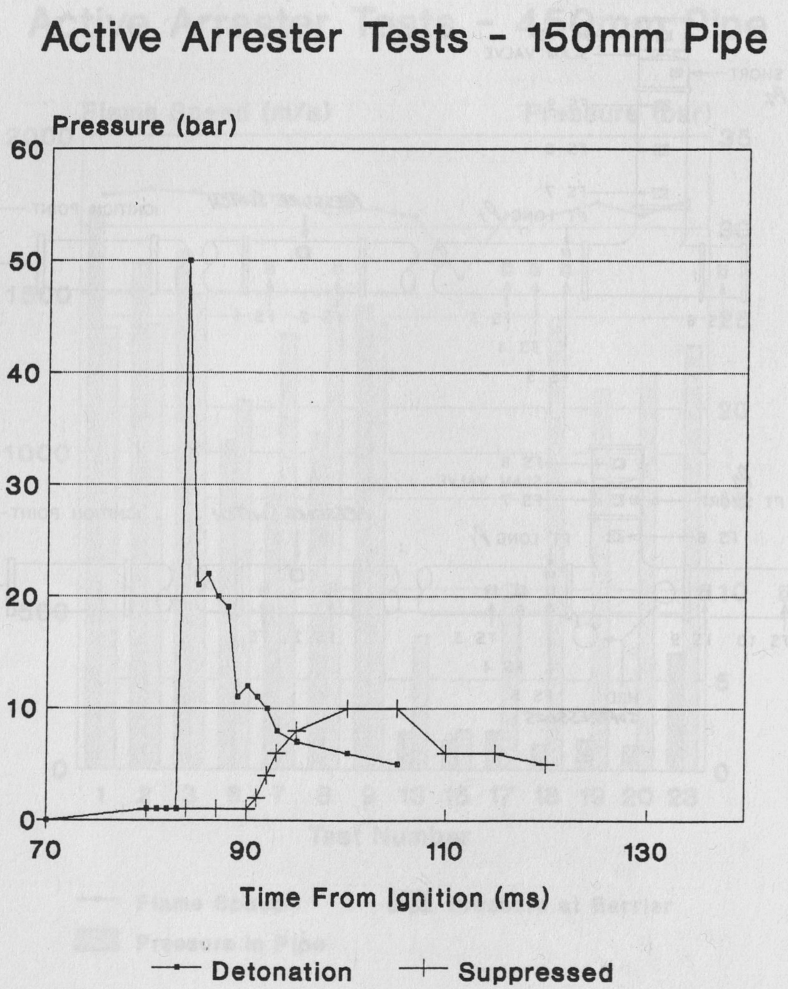


Figure 10

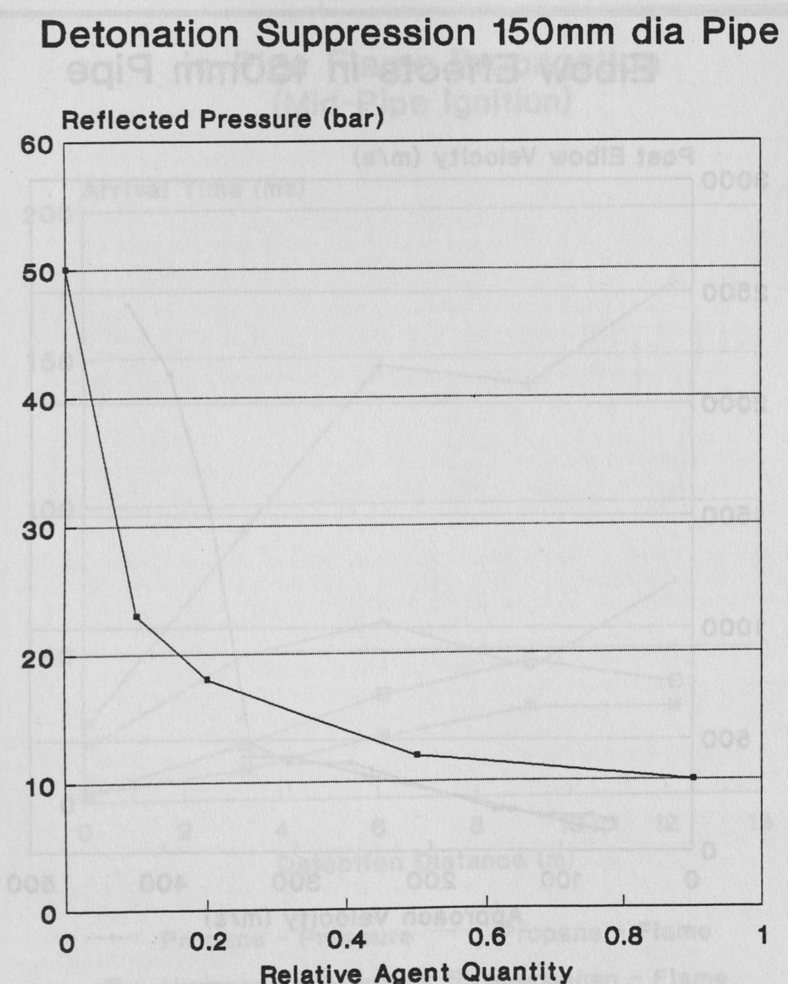


Figure 11

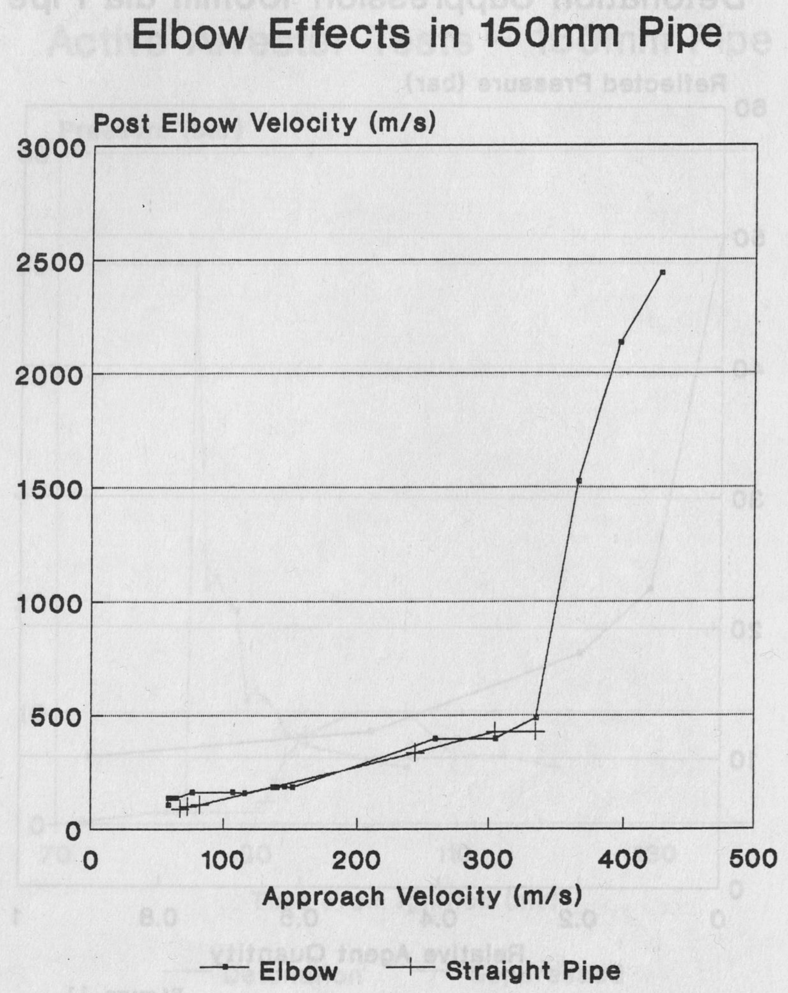


Figure 12

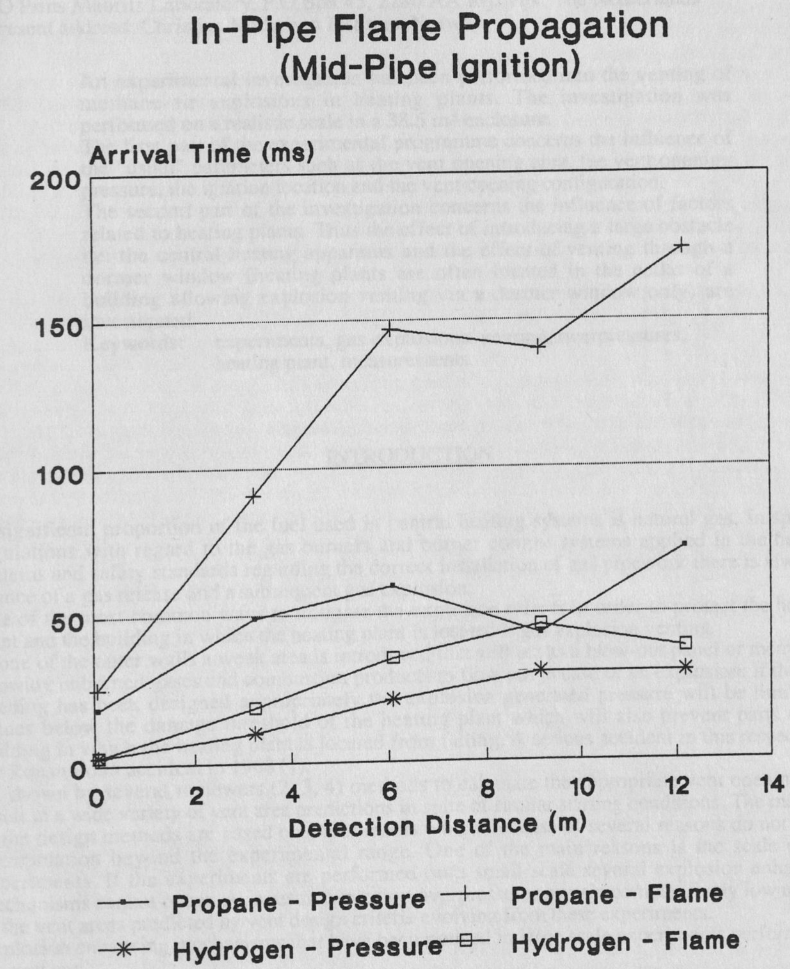


Figure 13