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D. D. Drysdale and R. Sylvester-Evans

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The explosion and fire on the Piper Alpha platform, 6 July 1988. A case study

By D. D. Drysdale[1] and R. Sylvester-Evans[2]

[1] *Department of Civil and Environmental Engineering, University of Edinburgh, Crew Building, King's Buildings, West Mains Road, Edinburgh EH9 3JN, UK*
[2] *RSE Consultants Ltd, 62 Palmerston Place, Edinburgh EH12 5AY, UK*

On 6 July 1988, at about 22.00, an explosion occurred on the Piper Alpha platform, an oil and gas production facility in the North Sea. Within seconds a major unstabilized crude-oil fire developed and all but the wellhead area and the lower parts of the platform were engulfed in smoke. The subsequent fire escalation was swift and dramatic with the first of three gas risers failing catastrophically after 20 min. In the disaster 167 persons lost their lives in what was the world's worst offshore accident.

The background to the investigation and the sources of evidence are reviewed. The available evidence is examined to explain the rapid fire escalation following the initial explosion. There follows a commentary on the way fire and fire dynamics are now being considered in the design and operation of UK offshore installations.

Keywords: Piper Alpha; offshore installations; fire; explosion; fireball; accident investigation

1. Introduction

The Piper field is located in block 15/17 of the North Sea, some 120 miles northeast of Aberdeen. The field was discovered in January 1973 and during that year the design of the platform commenced. The sea water depth is 140 m, and at the time the development and installation of the Piper Alpha platform represented a major step in both the development of the UK offshore resources and technology. The basic design of the topsides was based on those used in the Gulf of Mexico. Production of oil started in December 1976 when the first two wells were brought on-stream. During its early life the Piper Alpha platform proved extremely productive, producing up to 360 000 barrels of oil per day. At the time of the disaster, the oil production had dropped to some 125 000 barrels of oil per day, with many wells containing a high quantity of produced water. The oil was exported ashore through a sub-sea line 128 miles long to the purpose-built onshore terminal on the Island of Flotta in the Orkneys. The oil production from the Piper Alpha platform represented some 10% of the UK production from the UK sector of the North Sea.

Close by, the Claymore field had been discovered approximately a year after the Piper field and the Claymore platform, which was of a similar design to that of Piper, came on-stream in November 1977. The oil produced from the Claymore field was exported to Flotta through the same sub-sea pipeline. To the northwest of the Piper Alpha platform ran the gas export lines from the Frigg field to the onshore gas terminal at St Fergus. A booster platform known as the manifold compression platform no. 1 (MCP01) provided a convenient tie-in point to export gas produced

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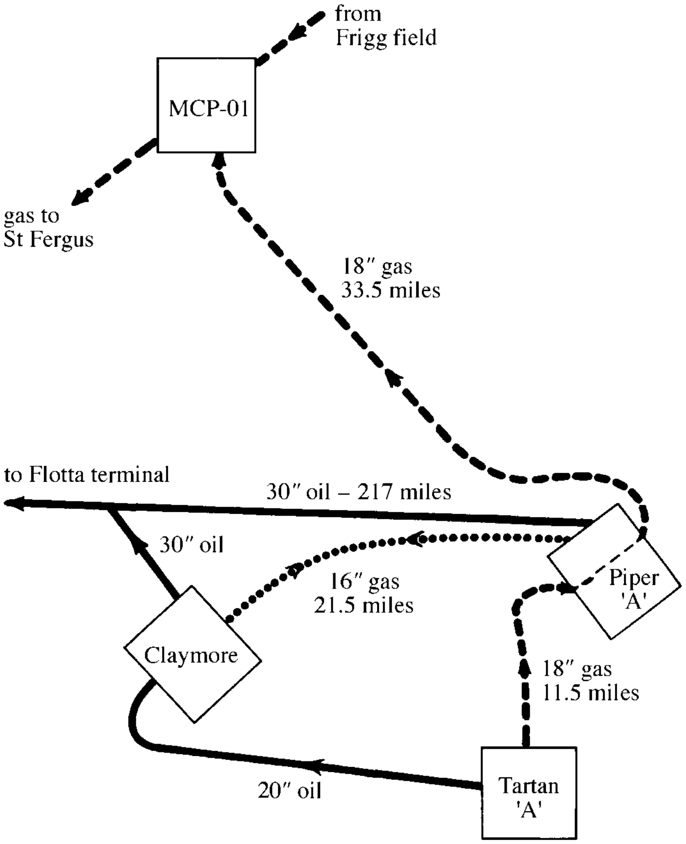

Figure 1. Piper Alpha: oil and gas pipelines.

at the Piper platform together with gas from the nearby Tartan A platform. Gas pipelines were thus installed linking Tartan to Piper and then Piper to MCP01. Further, a gas line linking Claymore to Piper was installed to provide gas, primarily, to the Claymore gas lift system. The overall network of oil and gas pipelines is shown in figure 1. The Piper Alpha platform thus became the focal point of the network. The historic development of the Piper field and adjacent fields also meant that the platform became the hub of the communications systems with land-based operations.

At the time of the disaster in July 1988 the operation and safety of the UK Offshore Oil and Gas Installations was under the control of the Department of Energy. The Secretary of State for Energy appointed Lord Cullen to hold a Public Inquiry to establish the cause and circumstances of the disaster. The Inquiry sat for 180 days and heard evidence from some 260 witnesses, who spoke in excess of six million words of evidence. The Public Inquiry was divided into two parts: part 1 concentrated on determining the cause and circumstances, while part 2 concentrated on the 'lessons to be learnt'. Lord Cullen's report was published in November 1990 and contained some 106 recommendations. These recommendations were founded on the belief that

> safety of personnel is fundamentally dependent on management systems;
>
> a systematic approach to safety is required;

systems must be reviewed and updated; and

systems must be audited to identify deviations and thereby be corrected.

Lord Cullen recommended that the Department of Energy be relieved of its responsibilities for offshore safety, and these should be transferred to the UK Health & Safety Executive. Further, one of his key recommendations was to completely revamp the offshore regulations from a prescriptive- to an objective-style regime. The cornerstone of this approach was the concept of a safety case for offshore installations. Lord Cullen believed that the safety case should be prepared by the operator to demonstrate, *inter alia*, that

(a) the safety management system (SMS) is adequate to ensure that the design and operation of the installation's equipment are safe;

(b) the potential major hazards of the installation and the risks to personnel have been identified and appropriate controls provided; and

(c) appropriate provision is made for ensuring, in the event of a major emergency, a temporary safe refuge and safe and full evacuation, escape and rescue for personnel on board.

The *Offshore Safety Case Regulation* came into force on 31 May 1993 and is supported by a trio of new regulations, namely the *Offshore Management and Administration Regulations* and the *Prevention of Fire, Explosion, and Emergency Response Regulations*, both of which came into effect in June 1995, and the *Design and Construction Regulations*, which came into effect in June 1996.

The cost of rebuilding the platform has been in excess of £1000 000 000 and the estimated cost to the overall offshore industry of safety-related modifications and the development of safety cases and followup work has been estimated to exceed £5 billion.

2. The platform

The west and east elevations of the topsides of the Piper Alpha platform are as shown in figures 2 and 3. (The directions refer to the platform coordinates; 'platform north' was 43° west of true north.) The production deck at the 84′ level† comprised four modules, A–D. The general layout is seen in figure 4. Module A, the wellhead module, was considered to be the most hazardous and accordingly the production modules were arranged so as to provide the maximum separation between module A and module D, which contained the various utilities, with accommodation areas located above. Module A comprised 36 wellheads which were used to control the flow of hydrocarbons and produced water from the wells. Module B was a production module where the separation of oil from other fluids took place and where the oil was pumped into the main oil line for transmission to Flotta. It contained the manifolds, test and main production separators and the main oil line export pumps.

Module C contained the original gas compression equipment whereby gas from the production separators was compressed for export ashore via MCP01. In the early 1980s, a gas conservation module had been installed at the 107′ level but at

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† $1' = 1$ ft ≈ 0.35 m.

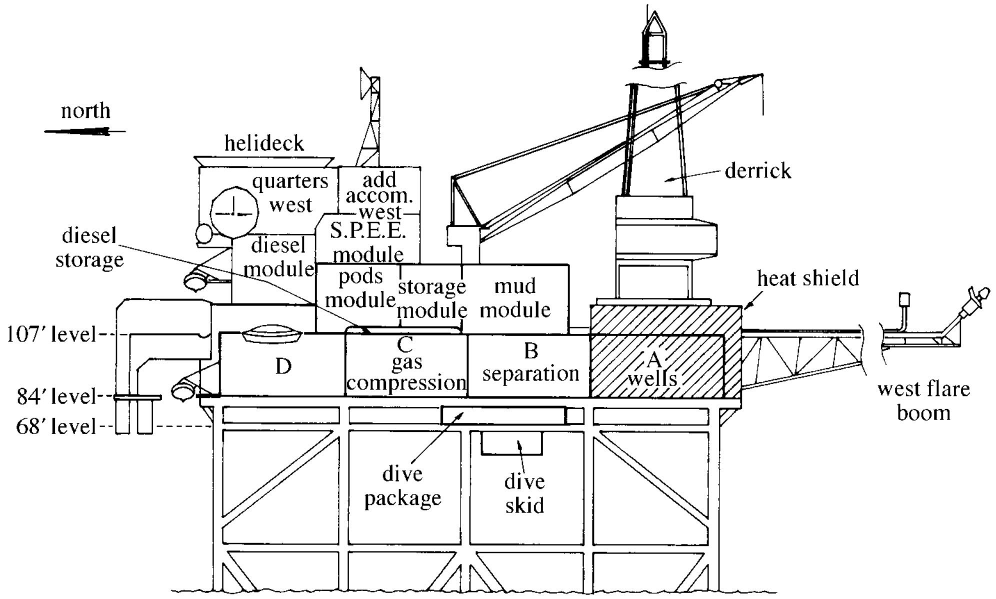

Figure 2. Piper Alpha: west elevation.

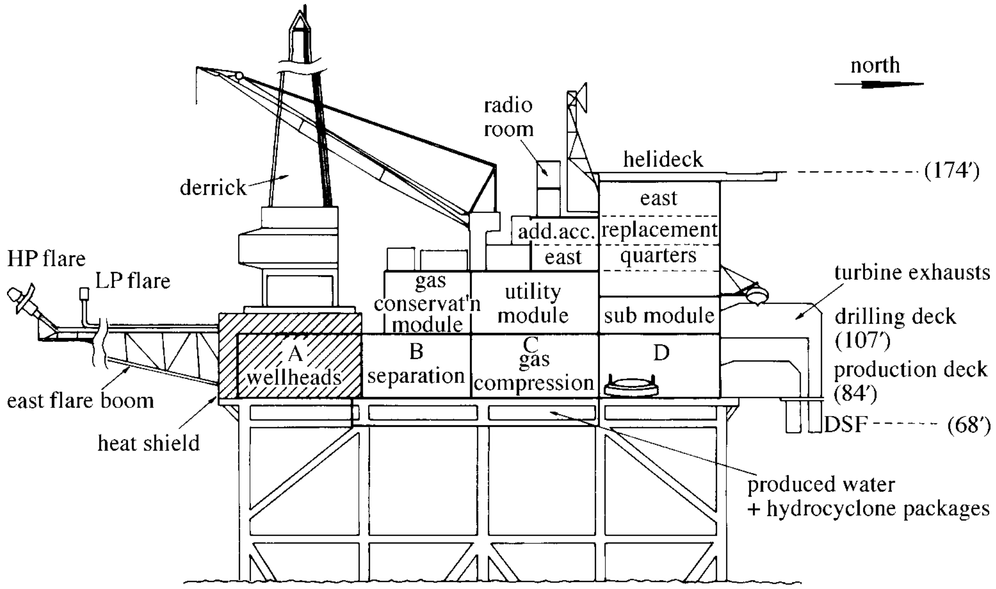

Figure 3. Piper Alpha: east elevation.

the time of the disaster this module was under maintenance and, therefore, gas was being processed and compressed only in module C. As part of this process, heavier components from the gas, known as condensate, were removed by letting the pressure of the gas down through a Joule–Thompson valve where the cooling effect caused condensate liquid to be formed. The condensate was collected in a drum which was located beneath module C at the 68′ level (see figure 5). The condensate was then

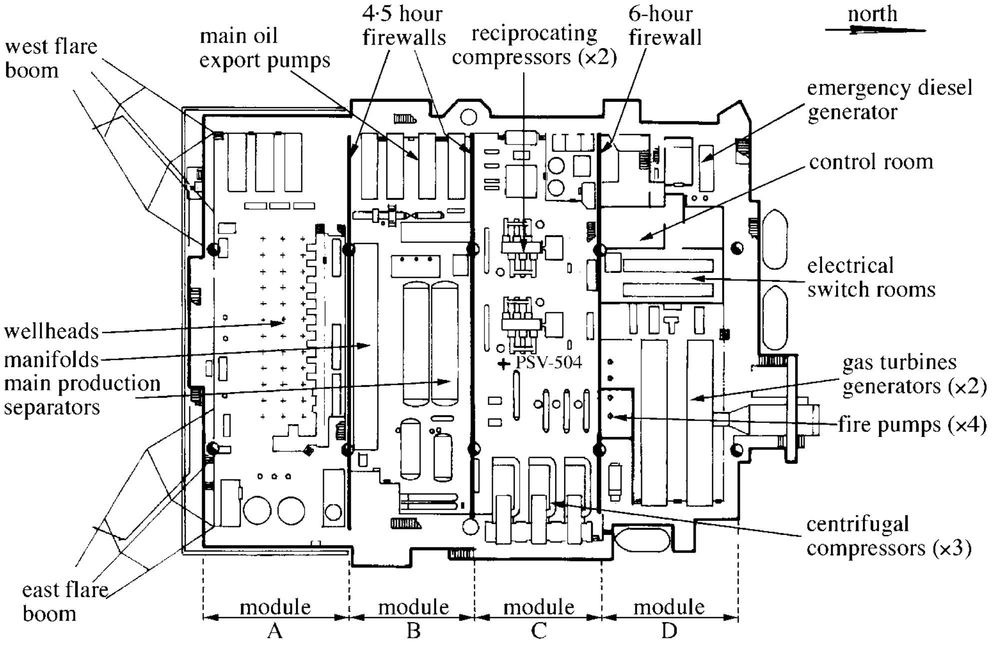

Figure 4. Piper Alpha: production (84′) level.

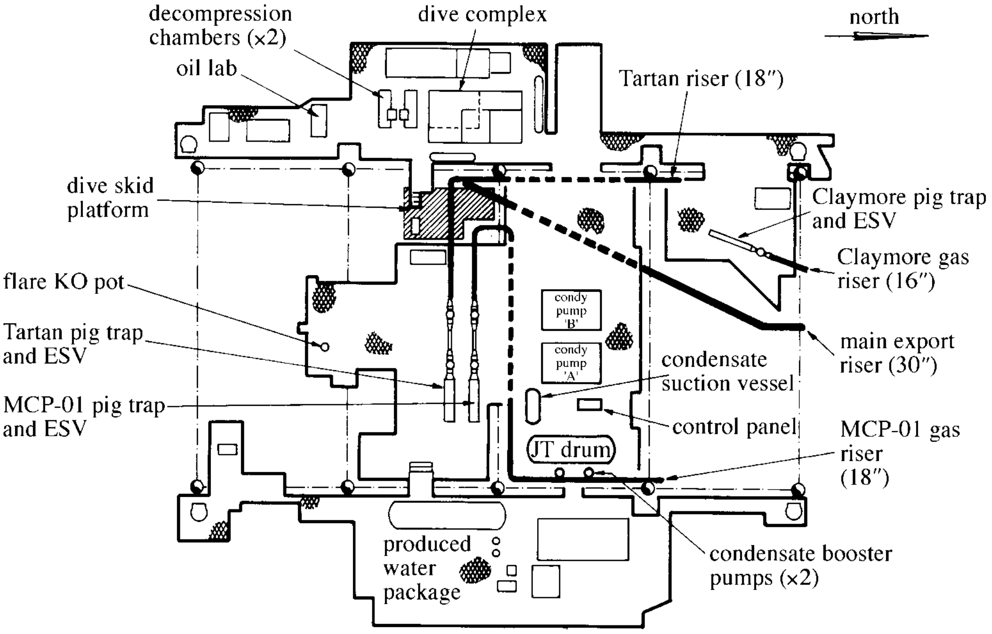

Figure 5. Piper Alpha: deck support frame (68′ level).

pumped back into the main oil line for export to Flotta by use of a booster and a condensate injection pump, of which there were two pairs, one normally on standby.

Module D was located on the north face/end of the platform and contained the control room, workshops, electrical power generation, the emergency diesel generator and some of the switchgear. The accommodation modules were located essentially above module D.

Modules A–D were separated by firewalls which were not rated for explosion overpressure. The firewall between modules C and D was specified for a 6 h fire rating while those between modules B/C and A/B were specified as a fire barrier for 4.5 h (see figure 4).

At the time of the disaster, the hydrocarbon inventory within the production modules was approximately 80 tonnes, this mainly being located in module B and, in particular, within the two production separators. In addition, there was a further 160 tonnes of diesel located in tanks above module C. The inventory on board the platform was small in comparison with the hydrocarbon inventories contained in the oil and gas pipelines, which were

main oil line to Flotta terminal	70 000 tonnes (approx.);
gas import from Tartan	450 tonnes;
gas export to MCP01	1280 tonnes;
gas import/export to Claymore	260 tonnes.

The location of the risers on the platform are shown in figure 5. Each pipeline had an emergency shutdown valve located in close proximity to its respective pig trap. Each valve was designed to be closed from the control room and provide a positive isolation of the pipeline from the platform.

3. Sources of evidence

In establishing the cause and circumstances of the disaster, a wide variety of sources of evidence were relied upon. These included: eyewitness accounts from the survivors, from persons on neighbouring vessels; data from nearby platforms; the recovery of the deceased; recovery of debris from the seabed; documentation available ashore; and the evidence of ‘back-to-back’ personnel who had recently been on Piper. What was unusual was that, due to the total destruction of the platform, the ‘scene of the accident’ had literally disappeared into the sea.

The evidence of survivors was crucial with regard to establishing the cause. There was vital evidence from the control room operator, who received a series of gas alarms from the eastern end of module C shortly before the explosion. However, following the explosion, due to the smoke plume no survivor gained access to either modules B or C, or saw the state of the B/C or C/D firewalls. Nevertheless, personnel were able to enter and move through module A and escape from the 68′ level shortly after the explosion.

Of the 135 bodies recovered, only four indicated death from burning. The vast majority died from inhalation of smoke and gas. The remainder died from injuries most likely sustained from jumping into the sea from heights of up to 174′. In the task of recovering as many of the deceased as possible, two accommodation modules were lifted from the seabed. Recovery was possible as they had fallen outside the main core of tangled debris centred on the remains of the platform jacket. A total of 79 bodies were found in the east replacement quarters (ERQ) (figure 3). This had been the main muster area for personnel onboard. It was a four-storey building which was lifted upside down from the seabed. Forensic examination of the building,

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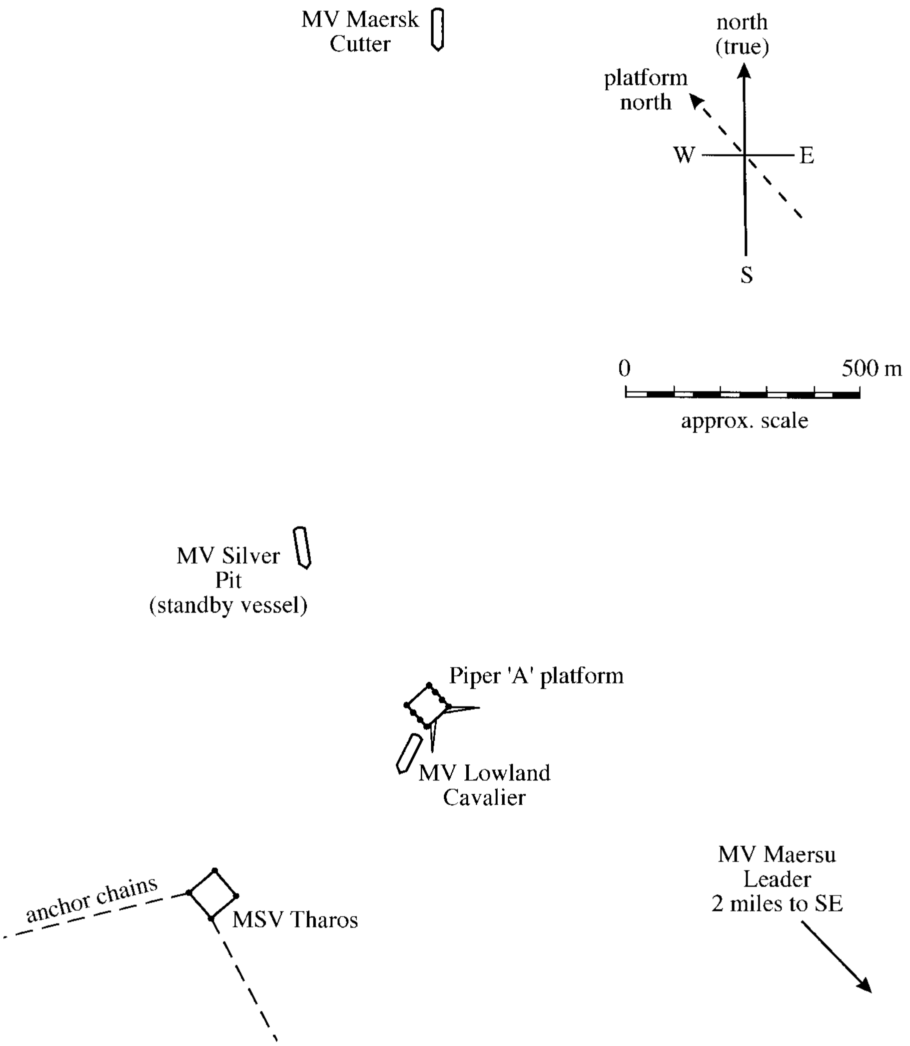

Figure 6. Piper Alpha: the locations of the principal support vessels.

together with the recovery and preservation of documentation from some of the offices, provided important sources of evidence.

Also of crucial importance were the eyewitness accounts of personnel on nearby vessels, the location of which are shown in figure 6. From these vantage points their evidence was vital to piece together the early fire development that occurred so quickly after the initial explosion. They also provided a wealth of photographic evidence.

Data from adjacent platforms assisted in determining when the pipeline risers failed on Piper and were also helpful in explaining why the high pressure flare continued to burn, at a steady rate, for at least 50 min following the initial explosion.

Appendix A lists the sources of evidence available to the investigation and indicates the nature and extent of the factual 'jigsaw' that had to be fitted together to determine the cause and circumstances of the disaster.

At the outset, one fact was clear; there had been 'an explosion'. The initial explosion appeared to originate in module C, affecting modules B and D. This is consistent with the initiation of gas alarms before the explosion. However, there were several potentially puzzling features of the subsequent rapid fire development which had to be explained, namely:

(i) the rapid development of a dense smoke plume within seconds of the initial explosion (this can be seen in figure 7);

(ii) a fireball emanating from the west face of module B some 15 s after the initial explosion, albeit all other indications were that the source of the explosion was in module C (figure 7);

(iii) the rapid development of a crude-oil fire in module B which continued to burn for a period which could not have been sustained from the available hydrocarbon inventory.

(iv) a fire seen on the north face of the platform that appeared to be connected in some way with the fire in module B (this can be seen in figures 7 and 8); and

(v) the early failure of the Tartan riser at 22.20.

4. Sequence of events

Lord Cullen based his conclusions on the eyewitness evidence available, supported by the technical investigations and studies of a number of experts who gave evidence at the inquiry. Key reports relating to the early stages were presented at the inquiry by Richardson & Saville (1989*a*, *b*), Davies (1989), Cubbage (1989), Bakke (1989), Cox (1989*a*, *b*), Palmer (1989), Drysdale (1989), Sylvester-Evans (1989), Standen (1989), Middleton (1989) and Tucker (1989). Lord Cullen's conclusions are fully described in the official report which placed the initial explosion in module C (Cullen 1990). Further, he concluded that on the balance of probabilities, the explosion was fuelled by a release of condensate from a blind flange that had not been fitted securely in module C. This flange was required because the pressure safety valve associated with one of the condensate injection pumps located at the 68′ level below, had been removed for maintenance. This made the pump unavailable for service. However, the evidence of survivors indicated that there was a clear intent and opportunity to restart this pump and, in doing so, admitting condensate to the pipeline leading up into module C where the blind flange was situated. An automatic gas-detection system gave an alarm in module C when the pump was initially pressurized. In the time available, the subsequent, more sustained repressurizing of the pump, which occurred shortly before the explosion, would have released condensate at a rate of the order of $3\,\mathrm{kg\,s^{-1}}$, producing a flammable mixture containing about 45 kg of condensate in the eastern half of module C. This event led to a flurry of gas alarms being received seconds before the explosion. The source of ignition could not be established.

Had the explosion been able to vent freely through the east and west face of module C, without failure of the firewalls, then a major disaster could have been averted with only a handful of people being injured. However, the congestion of equipment and pipe work produced a turbulent accelerating deflagration which generated an overpressure sufficient to cause failure and break-up of the B/C and C/D firewalls. The length of the module and the restricted vent area available would have exacerbated the situation.

The firewalls comprised a bolted lattice-work construction and were not designed as blast walls. It was the break-up of the firewall panels, and their ejection into the adjacent modules, that was the primary cause of the rapid fire development. Failure of the B/C firewall caused rupture of small-bore pipework in the metering skid area of module B and thereby initiated an immediate crude-oil release. It also caused disruption and failure of a 4 inch diameter condensate pipeline which passed through the B/C firewall, from module C into module B. The release of the contents of this line created the fireball photographed from the multisupport vessel (MSV) Tharos, the multisupport vessel located 550 m off the west face of the platform. Failure of the C/D firewall caused loss of all firewater supplies and emergency power, as these facilities were vulnerable to damage in module D by the missile effects created by the break-up of the C/D firewall. Further, the break-up of both the B/C and C/D firewalls enabled the free passage of smoke in a northerly direction through the production deck, the smoke arising from the early and rapid development of the crude oil fire in module B.

Only one eyewitness, namely, the master of the MV Lowland Cavalier, observed the combustion phenomena associated with the initial explosion. The stern of the vessel was located about 25 m from the southwest corner of the platform (figure 6), and the eyewitness was looking directly at the west face of the platform at the time of the explosion. He observed a blue flash, which appeared to come from module C, expand at low level across the west face of the production deck and retract back into module C. The sequence of events that led to the fire escalation and destruction of the platform after the initial explosion may be summarized as follows.

1. Residual condensate released from the blind flange assembly in module C continued to burn for a short period. This was seen by a person onboard the MSV Tharos. There is no evidence of any other major hydrocarbon fires occurring in module C immediately following the explosion. All high-pressure gas inventories in module C were depressurized automatically to flare.

2. A fireball which was observed burning above the condensate injection pumps below module C at the 68′ level immediately following the explosion was most likely caused by burning condensate vapour from the fuel-rich portion of the cloud being pushed downwards through pipe penetrations from module C to the 68′ level.

3. The break-up of the B/C firewall caused failure of small-bore piping associated with the metering skid in module B, resulting in a release of volatile crude oil which ignited immediately, giving a pool fire on the north side of the module in the metering skid. This fire produced a plume of combustion products and unburnt hot fuel–air mixture that was carried in a northeasterly direction by the prevailing wind through the production deck level. The movement of the plume through the platform to the north face was enhanced by the structural beams which helped to channel the smoke in this direction.

4. Some 15 s after the initial explosion, the 4 inch diameter condensate pipeline failed, releasing some 75–100 kg of condensate into the existing fire and creating

Figure 7. Fireball seen emanating from west face of Module B (cf. figure 2). The HP flare is seen to the right and the fire on the north face is seen to the left. Photograph taken some 15 s after initial explosion.

a fireball at the west face of module B. This was captured on film by a mobile diving unit pilot from the deck of MSV Tharos (figure 7). The size and duration of the fireball are discussed further in § 6.

5. The overpressure created by the failure of the condensate pipeline together with the development of the fireball was sufficient to expel unburnt fuel-rich gases developed from the fire in module B, together with residual fuel from module C, out towards the north face so as to produce a fire beneath the ERQ at the 133′ level on the north face of the platform. This can also be seen in figures 7 and 8.

6. For some seconds after the fireball started to lift from the west face, flames could be seen at the 68′ level immediately below module B (figure 8). This is consistent with burning condensate vapour being pushed through the main oil line (MOL) pipe penetration.

7. The fire in module B escalated, most likely being fuelled by backflow of gassy crude oil through the ruptured condensate pipeline where it tied in to the MOL. The crude-oil fire then developed across the full width of module B.

8. The A/B firewall remained essentially intact and therefore major fire escalation into module A was delayed.

Figure 8. Lift off of fireball; photograph taken some 2 s after figure 7. Transient flame visible at and below the 68′ level.

9. Within a minute of the initial explosion, crude oil was seen running down the MOL at the 68′ level and supporting structures from module B above. It was starting to flame. The flow of oil worsened and the area beneath module B became impassable after about 5 min.

10. It is most probable that the emergency shutdown valve (ESV) on the MOL failed to fully close and backflow from the MOL contributed to fuelling the fire in module B.

11. Many of the persons on board were already in, or attempted to reach, the muster station at the top level of the ERQ, to await helicopter evacuation. Access to all lifeboats was impossible due to smoke impairment. Helicopter access to the helideck was also impossible.

12. The fire in module B continued to burn steadily with it extending to the south side of module C. However, the overflow of oil from module B, particularly that running down the MOL, created a running fire which pooled on the dive skid at the 68′ level. The dive skid was normally grated but had been covered by rubber matting to assist the diving operations. The subsequent pool fire that developed heated the Tartan riser located directly above the dive skid.

13. At 22.20, flame impingement had heated the riser sufficiently to weaken the pipeline and it failed catastrophically, resulting in a massive fireball that engulfed the platform and leaving a torch flame to develop beneath the whole

platform. In the first minute, some 30 tonnes of high-pressure gas was consumed in the fireball and initial torch flame.

14. Prior to the failure of the Tartan riser, the breathable atmosphere within the ERQ had deteriorated badly and people had already decided to leave and seek shelter elsewhere on the platform or escape.

15. The Tartan pipeline continued to sustain a major fire underneath the platform for the next 30 min with the fire in module B continuing to burn at a constant rate.

16. During this period, if not before, the diesel tanks located above module C were breached contributing further hydrocarbon to fuel the fire.

17. At 22.50, the MCP01 riser was breached and a major fireball developed, which was described as 'an upside-down mushroom'. The fireball reached the aft face of the Tharos, which was by then 50 m from the platform.

18. Throughout this period the high-pressure flare had been burning steadily following depressurization of equipment within minutes of the initial explosion. This source of fuel was most probably the inventory of the Claymore gas pipeline via its ESV, which was suspected not to have closed. Further, it is possible that a small contribution to the HP flare came from the MCP01 pipeline via its ESV which may not have been fully seated.

19. Between 23.00 and 23.30, the Claymore and MOL risers failed, the derrick collapsed and the centre of the platform sagged. Shortly thereafter, the main accommodation block (ERQ) toppled into the sea.

5. Severity of the initial explosion

Only the master of the MV Lowland Cavalier saw the actual combustion process associated with the initial explosion in module C. As he was watching the west face of the platform, he saw a blue flash emanate from module C and expand at low level across the face of the production deck level. There would have been a fuel-rich mixture in the vicinity of the leak source in the eastern half of module C. As the explosion developed at the eastern end of the module, unburnt fuel was moved in a westerly direction. By the time the mixture was expelled from the west face it burnt as a fuel-lean mixture and may also have expanded into module B through the breached B/C firewall.

The severity of the initial explosion in module C probably caused limited damage within that module. However, it caused extensive damage to the adjacent modules due to the break-up of the firewall panels. These acted as high-speed energetic missiles causing widespread loss of all utilities and emergency systems, as well as the initial fire development in module B (see § 7).

The size of the flammable cloud that caused the original explosion was relatively small, occupying only the lower eastern half of module C, amounting typically to 10% of the volume of the module. Had it been substantially greater, then a turbulent flame would have been seen venting across the whole of the west face of the module and different effects would have been witnessed at various locations on the platform. The size of the original flammable cloud was estimated to be typically in the range of 40–60 kg (Cubbage 1989; Mitcheson, personal communication).

Based on simple empirical equations (Butlin & Tonkins 1974), the explosion overpressure in module C was estimated to be in excess of 0.2 bar and probably in the range 0.4–0.7 bar (Cubbage 1989). This approximate range was refined by detailed computer modelling of how the explosion could develop from a flammable cloud of 45 kg of condensate located at the eastern end of the module. The maximum overpressure was estimated to be of the order of 0.3 bar. This was still surprisingly high for a relatively small flammable mass and for an enclosure which was nominally open at each end. However, studies have shown that turbulence can induce flame acceleration, which can create overpressures under favourable conditions (Harrison & Eyre 1987; Hjertager *et al*. 1988). The congested space towards the east end of module C, where there was much equipment and pipework, would present the conditions necessary to generate turbulence in the unburnt flammable vapour–air mixture as it was pushed ahead of the propagating flame front. The computer model used the computational fluid-dynamics code FLACS developed at the CMI, Norway (Bakke & Bjerketvedt 1993). It confirmed the mechanism and was in essential agreement with the amount of condensate vapour that is likely to have been involved and the damage effects created by break-up of the firewall (Palmer 1989).

6. Condensate fireball

It was important to establish the source of fuel for the fireball photographed emanating from the west face of module B (Drysdale 1989). The shape and symmetry of the fireball suggested that the fuel was a flashing liquid under pressure. The colour, together with the uniformity of mixing within the fireball, supported this view. There was no evidence of smoke generation and there were significant momentum effects to cause the fireball to be ejected from the west face of the platform. A photograph of the fireball is shown in figure 7.

Its characteristics did not match those of a vented gaseous explosion nor the high-pressure release of a volatile hydrocarbon liquid. The only source of light 'flashing' hydrocarbon available to fuel the fireball at the west end of module B was the 4 inch diameter condensate line that tied in to the MOL. The condensate line originated at the booster pump on the 68′ level, penetrated through the deck of module C and passed through the B/C firewall into module B about 10 m from the west face. It then ran parallel to the firewall; there were two further right-angle bends before it met the MOL. A non-return valve was fitted close to the tie-in point. Analysis of the available energy associated with the panels created upon break-up of the B/C firewall showed that there was ample energy available to cause disruption and failure of the 4 inch condensate pipeline (Palmer 1989).

The inventory of condensate in the pipeline was estimated to be approximately 80 kg, although it might have been larger if valves had not provided a positive isolation and thereby permitted additional hydrocarbon to enter the line. The question was whether the fireball size and duration was consistent with the available inventory within the 4 inch diameter condensate pipeline. The difficulty with using existing theoretical or empirical relationships to predict the size and duration of the fireball was that all refer to completely unconfined releases, whereas the release in module B was partly confined.

The second difficulty was that there was no clear method of determining the depth of the fireball. The dimensions, as measured from the photograph, indicated a height of 33 m and a width of approximately 23 m. From these dimensions the average diameter would have been 28 m. As the fireball illuminated much of the end of the module of the platform it was clear that it was ejected from the west face by at least some 20 m. However, the extent of burning within module B was unknown; therefore, it was quite possible that the average diameter of the fireball could have been smaller as its dimensions were scaled against the known dimensions of the west side of the platform.

Assuming the average fireball diameter was 28 m and using the empirical equation developed by Roberts (1981/82),

$$D = 5.8M^{1/3},$$

where D is the diameter of the fireball in metres and M is the mass of fuel in kilograms, then the mass of fuel would be approximately 112 kg. Using the same empirical equation, a release of some 80 kg is predicted to generate a 25 m diameter fireball. This offered a reasonable match.

Although the Roberts equation was based on a theoretical consideration of the fireball dynamics, it correlated well with contemporary data from experimental and accidental releases. More recently Dorofeev *et al.* (1993, 1995) reported on a series of large-scale experiments involving the burning of fuel-rich clouds. The fuels involved deflagrations and detonations of gasoline, kerosene and diesel fuel, and involved a fuel mass that varied from 0.1 to 100 tonnes. The size of the Piper fireball was therefore at the lower end of the range. Further, these large-scale tests involved the generation and ignition of the heterogeneous fuel clouds by explosive charges. Accordingly, these represented a significant difference in the initial conditions compared with that of Piper. Dorofeev's empirical equations for a deflagration of gasoline, and of diesel fuel/kerosene, can be expressed, respectively, as

$$D = 4.47M^{0.34} \quad \text{and} \quad D = 5.32M^{0.33}.$$

Assuming an average fireball diameter of 28 m, the mass of fuel involved is predicted to be between 150 and 220 kg. The fireball diameter that would correspond to fuel release of 80 kg would be between 20 and 23 m. Again, given the uncertainty of the depth of the fireball, the fireball size is generally consistent with the available inventory in the pipeline.

A similar approach may be adopted when examining the duration of the fireball. Examination of the photographic evidence suggested that the visible fireball had burnt out within 4 s (figure 8). A correlation derived by Roberts (1981/82) predicts a duration of between 2 and 4 s, while that of Dorofeev *et al.* (1995) gives a duration of between 3 and 4 s. The predicted results are therefore consistent with the inventory of the 4 inch diameter condensate pipeline. In any event, the duration would be expected to be somewhat longer because of the partial confinement associated with the initial release.

The above example shows how relatively simple empirical equations can be used to confirm the consistency, or otherwise, of eyewitness observation arising in accidents. However, it must be remembered that considerable uncertainties do exist with the use of such expressions and, therefore, care and circumspection are required. The objective in any such investigation is to ensure that one achieves the best fit for all the factual elements of the 'jigsaw' and that there is an overall consistency in any argument.

Regarding the cause for the delay of some 15 s after the initial explosion before generation of the fireball, a number of possibilities were examined. Clearly, the 4 inch diameter condensate pipeline was not severed immediately by the missiles otherwise there would have been no significant delay. However, the available energy was sufficient for severe disruption of the pipeline to have occurred (Palmer 1989). The delay could have been caused by additional stresses being applied to the pipeline due to movement of other equipment and piping, or by the reaction forces associated with a small leak. An alternative theory was advanced to suggest that the initial leak from the pipeline was crude oil, the most likely point of fracture being close to the tie-in point with the MOL (Drysdale 1989). It was only after pressure in the MOL subsided, as the main oil-line pumps run down, that the release of condensate occurred. In any event, the qualitative interpretation of the characteristics of the fireball, supported by the application of empirical equations, was sufficient for Lord Cullen to conclude that the fireball was caused by the failure of the 4 inch diameter condensate pipeline.

7. The crude-oil fire in module B

The fire in module B continued to burn with no apparent reduction in intensity, at least until the third explosion at approximately 22.50. It was important to know if this could have been sustained by the inventory of crude oil in the separators, or whether it was being fuelled by leakage from the main oil line due to failure of the ESV. The maximum inventory in the separators is known to have been 50–55 tonnes. The rate at which the remaining quantity would be consumed would depend on the surface area of the pool formed on the deck of the module, and the rate of burning of the crude. Babrauskas (1983) has suggested that, in the open, stabilized crude oil would tend to burn at a maximum rate of up to *ca.* 0.05 kg m^{-2}. As the crude oil in the separators was not stabilized (it had a flashing fraction of *ca.* 7%), the effective burning rate would have been somewhat greater—perhaps as high as 0.08 kg m^{-2}. In a confined space considerably higher rates would be expected as a result of radiant heat feedback from the flames and hot gases deflected and confined by construction of the module. Moreover, the hot metal surfaces would contribute heat transfer to the pool by conduction through the deck plates, etc. In experimental work, burning rates of liquids enhanced by a factor of up to eight have been observed (Bullen & Thomas 1979); here we will assume a factor of two to give a conservative burning rate of 0.16 kg m^{-2}. On this basis, 50 tonnes of the unstabilized crude oil would have taken more than 50 minutes to burn out only if the pool area was *less* than 100 m^2. As there seems to be no reason why the pool of oil would be confined to such a small proportion of the total deck area (675 m^2), it is concluded that there must have been a continuing leakage of crude oil into the module from the MOL. This is certainly consistent with the sudden escalation of the fire that was apparent once the fireball had lifted from the face of module B.

8. Lessons learnt

The Piper Alpha disaster has caused the offshore industry worldwide to reappraise many safety aspects associated with the design and operation of both fixed and mobile offshore installations. A considerable effort and expense has been incurred in the mitigation of effects from explosions and fires. Much of the expense has been incurred on older platforms and rigs where it has been necessary to implement a consistent package of remedial measures so as to reduce the risks to as low as reasonably practicable. Examples of remedial measures for existing platforms, and design measures for new installations include, *inter alia*, the following.

A. Isolation of hydrocarbon inventories. Considerable effort has been directed towards the effective isolation of pipeline hydrocarbon inventories from fixed installations. This has included the installation of the subsea isolation valves and the relocation of ESVs to locations on the installation which are protected and can survive major accidents. Additional ESVs have also been provided. The overall reliability of these systems, as well as the survivability, have become important issues. Efforts have been made to minimize hydrocarbon inventories and, for high-pressure equipment, rapid depressurization systems are being fitted, although on existing facilities the materials of construction can represent serious limitations. Dump systems involving the rapid disposal of hydrocarbon liquids have also been considered.

B. Mitigation of explosion effects. Analysis of potential explosions in modules have revealed that in many situations significant overpressures can be generated and that bulkheads/firewalls would fail as a result. Remedial measures that have been implemented include, for example, provision of blast walls and additional relief panels. For new designs, considerable care is now taken with regard to equipment layout and minimizing plant congestion so as to reduce the potential for flame acceleration and generation of overpressures. Of crucial importance is the prevention of hydrocarbon leaks in the first place. While the industry recognizes the importance of prevention, over a two year period up to October 1994 some 523 releases of hydrocarbons were reported to the Health & Safety Executive, 70% of which involved releases of more than 10 kg of hydrocarbon. Fortunately, in the light of the relatively high frequency of loss of containment incidents, the frequency of ignition was only 3% (HSE 1996).

C. Fire protection. The removal of prescriptive legislation by the HSE has allowed the industry to adopt a more sensible mixture of active and passive fire protection so as to achieve their objective. This has been particularly important with regard to the implementation of remedial measures on existing facilities.

D. Temporary refuge. Lord Cullen recommended that each installation has an area, or areas, which could act as a temporary refuge in the event of a major accident. The intent was to protect people on the installation from hazards of explosion, fire, heat, smoke, toxic gas or fumes in any period while they may need to remain on the installation following an incident which was beyond their immediate control and, thereby, enable people to be evacuated safely where necessary. The subsequent safety case regulations have required the operator ('duty Holder') to lay down performance standards for the temporary refuge and the access routes therefrom, together with the embarkation points, so that such facilities can be shown to be effective following an incident. In some cases this has meant a change of philosophy for companies in handling personnel onboard during an emergency and has presented a challenge to ensure that the temporary refuge is fully integrated into the emergency plan for the installation.

E. Control of smoke hazard. The hazards of smoke were not fully appreciated by the offshore industry prior to the Piper Alpha disaster. Many of the temporary refuges initially selected by companies were found to be poorly sealed and would have become rapidly impaired by smoke in the event of a major fire on the installation. Considerable effort has been taken to mitigate the effects of smoke, such as the pressurization of secure areas, the sealing of wall penetrations, provision of air locks and installation of barriers and screens. Also, water sprays have been used to control the movement of smoke. Other measures include the provision of smoke hoods to persons, and improvements in the emergency lighting and signing of access and escape routes.

As can be seen, considerable improvements have been made over the past nine years to mitigate the effects of major accidents on an offshore installation. The industry has also reviewed its safety management systems and is now in a position to demonstrate the method by which it controls safety throughout the lifetime of an installation, from its design through to its decommissioning. Initial indications show that the risk of a major disaster offshore has been reduced by about 90%. If this is indeed shown to be statistically correct, then the lessons of Piper will have been learnt.

The authors would like to acknowledge the work of all the technical experts who gave evidence before Lord Cullen's Public Inquiry and Mrs Lesley Gray of Paull & Williamsons for permission to use photographs taken by Mr Miller onboard the MSV Tharos.

Appendix A. Sources of evidence

(a) Source: survivors (61 out of 226)

Pre-explosion

1. Status of operating equipment and maintenance work ongoing prior to explosion.
2. Witness accounts of events leading up to the explosion, particularly attempts to restart the condensate handling facilities from about 21.45 to 22.00.
3. Gas-detection alarms, received in the control room, indicating low- and high-gas concentrations in the eastern half of module C only.
4. Tripping of centrifugal compressors as indicated in the control room. No other process alarms received except one associated with the condensate handling facility.
5. Increased flaring heard/seen shortly before the explosion.
6. Noises heard by various personnel immediately before the explosion.

Explosion effects on survivors

1. Overpressure and/or dynamic wind effects: to personnel; in the control room; just below the west face of module C; and at the bottom of stairs leading from module C to the 68′ level.
2. Severe vibration felt by persons at: boat bumper (20′ level); dive complex (68′ level) and dive skid (58′ level); maintenance workshop (84′ level); mud module (107′ level); and the cinema and parts of the accommodation (133′ level+).
3. General vibration felt by all other survivors.

Post explosion (until 22.20)

1. Debris seen ejected from west face of platform.
2. Damage to gantry and debris seen at west face of module C.
3. No direct observations were made of modules B or C or of extent of damage to the B/C and C/D firewalls due to smoke logging.
4. Extensive damage to control room and smoke ingress from module C through breach of the C/D firewall and damage to mechanical workshop and tea room (84′ level).
5. Fire development at west face of modules B and C (84′ level).
6. Complete smoke logging of north face of platform and module D (84′ level).
7. Extensive disruption to ‘loose’ fittings in modules (107′ level) and in accommodation areas and cinema.
8. Rapid smoke penetration and impairment of breathable atmosphere in the ERQ.
9. Serious smoke impairment of pipedeck (133′ level) above and to the north of module B.
10. A/B firewall remained intact.
11. Burning ‘fireball’ seen above the condensate pumps at the 68′ level, and directly beneath module C, immediately after explosion.
12. Damage to decompression chamber door (68′ level).
13. Extensive damage to internal ‘loose’ fittings of dive complex office and workshops (68′ level).
14. Burning debris and falling oil then ‘burning oil’ onto the 68′ level from module B above.
15. Some 30 survivors escape from the 68′ level at the northwest corner of platform via a knotted rope prior to 22.20.

Post explosion (after 22.20)

1. Platform engulfed in a major fireball at about 22.20 (later shown to be failure of the Tartan riser).
2. Subsequent progressive collapse of structure and failure of process equipment and risers; further 31 survivors escaped during the period between 22.20 and 23.15–23.30.

(b) *Source: recovery of deceased*†

1. A total of 135 bodies were recovered; 79 bodies from the ERQ and a further 56 bodies from the sea or seabed.
2. Post-mortem results indicated: 11 deaths from drowning; 11 deaths from injuries, including burns; 109 deaths from inhalation of smoke and gas; 4 deaths where cause of death was not ascertained. (Death was caused by burn injuries in only four cases.)

(c) *Source: eyewitnesses off platform*

MSV Tharos

1. A semisubmersible multisupport vessel, located some 550 m off the west face of Piper.

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† 165 out of 226 aboard Piper and two aboard the Sandhaven’s fast-rescue raft died.

2. One eyewitness was photographing Piper at the moment of the explosion. He first observed light coloured smoke coming from the west face of module C. His first sequence of photographs, taken some 15 s after the explosion show: a fireball emanating from west face of module B; major smoke plume engulfing the northern half of platform; a fire on the north face of the platform; and a major crude-oil-fuelled fire in module B after the fireball.
3. Several eyewitnesses, whose attention was drawn immediately to the platform by the shudder/noise felt and heard aboard, observed within the first 10–15 s (before the fireball photographed): residual fire, high up in the central portion of module C; a developing fire within and on the north side of module B; smoke emanating from the west face of module B; and smoke coming from, apparently, the east end of module C.
4. Many eyewitnesses observed the subsequent fire development in module B after the fireball.
5. The helicopter from the MSV Tharos was airborne at 22.11. Two minutes later it was reported that no flames were visible on the east side of the platform and Piper's helideck was obscured by smoke; subsequently, photographs were taken by crew.
6. The MSV Tharos moved in towards Piper. By 22.50 it was about 50 m off the west face of the platform but then withdrew after failure of the MCP01 riser which resulted in a fireball partly engulfing the stern of the vessel.

MV Lowland Cavalier

1. A support vessel engaged in pipe trenching operations, the stern of which was located some 25 m off the southwest corner of Piper.
2. Increased rate of gas flaring observed at about 21.50 (photographed) and again some 2 min before the explosion.
3. The master observed a 'blue flash' at low level across the 84′ level of the west face, followed by hearing and feeling the explosion shockwave. Several seconds later he saw a small fire develop at the north side, within module B.
4. Several eyewitnesses saw smoke emerge from module B and a fire develop within that module. One eyewitness photographed module B some 40 s after the explosion.
5. Another eyewitness photographed the platform from about 22.10 onwards, including the failure of the Tartan riser at 22.20.
6. The vessel moved away from the platform so as to launch her workboat.

MV Silver Pit

1. The Piper standby vessel, located some 400 m northwest of the platform.
2. One eyewitness saw debris fly past the vessel at the time of the explosion.
3. The MV Silver Pit's fast rescue craft (FRC) was launched at 22.02.

MV Maersk Cutter

1. A supply vessel, acting as anchor handling vessel for the MSV Tharos, located 1600 m northeast of platform.
2. The master's attention was attracted by 'wave-slap' beneath the vessel (vibration), most likely caused by a pressure pulse travelling through the water. His initial observation was of a light grey smoke hanging off the east face of module C followed by smoke coming from that module, changing from a light to dark colour as it did so.
3. The vessel moved towards Piper to fulfil fire-fighting duties. No flame was seen at the east face of module B for at least the first 4 min.

MV Sandhaven

1. A standby vessel for a drilling rig located 4.5 miles from Piper. No immediate eyewitness observations. The FRC from the MV Sandhaven was destroyed subsequently, with the loss of two crew, when the MCP01 riser failed at 22.50.

MV Maersk Leader

1. A supply vessel, acting as anchor handling vessel for the MSV Tharos some 2 miles south-east of the platform.
2. Eyewitness videoed the fire development from 22.05/10 onwards, capturing the Tartan riser failure at 22.20 and aftermath of subsequent riser failures. Video shows steady flaring of gas from Piper flare until about 22.50.

Other vessels

1. Many other vessels joined the search and rescue operations throughout the night of 6/7 July 1988.

(*d*) *Source: damage to nearby vessels*

MV Lowland Cavalier

1. Glass windows located at the stern of the vessel and facing the platform were blown out of their grommet seals.
2. The chief engineer was blown into the superstructure of the bridge bulkhead by the shockwave.

(*e*) *Source: nearby platforms, connecting pipelines and Flotta oil terminal*

Claymore

1. Located some 22 miles west of Piper.
2. Visual observations were made of fire on Piper.
3. Claymore continued exporting oil to the MOL until 23.10.
4. Depressurization of Piper–Claymore gas pipeline commenced at 23.00 at Claymore, but riser failed on Piper at about 23.15.
5. Data stored on the Spectra-tek metering and telemetry system giving the pressures and flow rates associated with all oil pipelines prior to the explosion, and certain pressures after the explosion.
6. Chart recordings of Claymore gas pipeline flow rates/pressures and log books.

Tartan

1. Located some 12 miles southwest of Piper.
2. Depressurization of Tartan–Piper gas pipeline commenced at 22.20 at Tartan, but riser failed on Piper at about the same time.
3. Chart recordings of Tartan gas pipeline pressures and log books.

MCP01

1. Located some 34 miles northwest of Piper.
2. The riser of the Piper MCP01 pipeline failed on Piper at about 22.50 and the pipeline depressurization commenced on MCP01 at about 23.00.
3. Installation logs.

Flotta oil terminal

1. Control room staff observations of loss of telemetry and low-flow alarms received at Flotta.
2. Chart recordings of drop in flow being processed at the terminal, log books and records.

(*f*) *Source: recovery of debris*

Hardware

1. Recovery of limited hardware; essentially loose items which ‘fell’ free of the main structure such as containers, structural debris, remains of lifeboats/liferafts, etc.
2. No process equipment could be recovered, except the methanol pump.
3. Video recordings of seabed debris.

Accommodation

1. Recovery of additional accommodation west (AAW) and the ERQ followed by forensic examination of: metal fittings to determine external temperature; paint layers to determine internal/external temperature; analysis of smoke deposits to determine principal hydrocarbon source and means of ingress and movement of smoke; and fire protection systems (active and passive).
2. Cause and circumstance for flame ingress and fire development.

Documentation

1. Recovery and preservation of documentation kept in the Offshore Installation Manager and Production Ops Superintendent’s Office of the ERQ including: daily logs compiled by Operation Superintendent, Deputy Ops Superintendent and Maintenance Superintendent, last entries being for 5th July 1988; handover Logs for operations staff; permits to work; and various operational/maintenance procedures, records, reports, etc.

(*g*) *Source: documentation held on the ‘beach’ (ashore)*

1. All company documentation relating to the design, construction, operation and maintenance of Piper, including, for example: daily reports from each department, operations, maintenance, drilling, project services, last reports being of 5 July 1988; verbal production report telephoned in at 16.00 on 6 July 1988; departmental reports and minutes; more than 8000 drawings of facilities; process flow simulations; and design specifications of vessels, equipment, piping, etc.
2. Selected documentation from certifying authority.
3. Inspection reports, etc., from Department of Energy inspectors.

(*h*) *Source: back-to-back personnel*

1. The ‘back-to-back’ personnel who had changed over with those on Piper at the time of the explosion. The last helicopter left the platform at about 17.00 to change out personnel. Back-to-back personnel provided factual evidence as to the status of plant and equipment, together with operational intent and expectations.

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