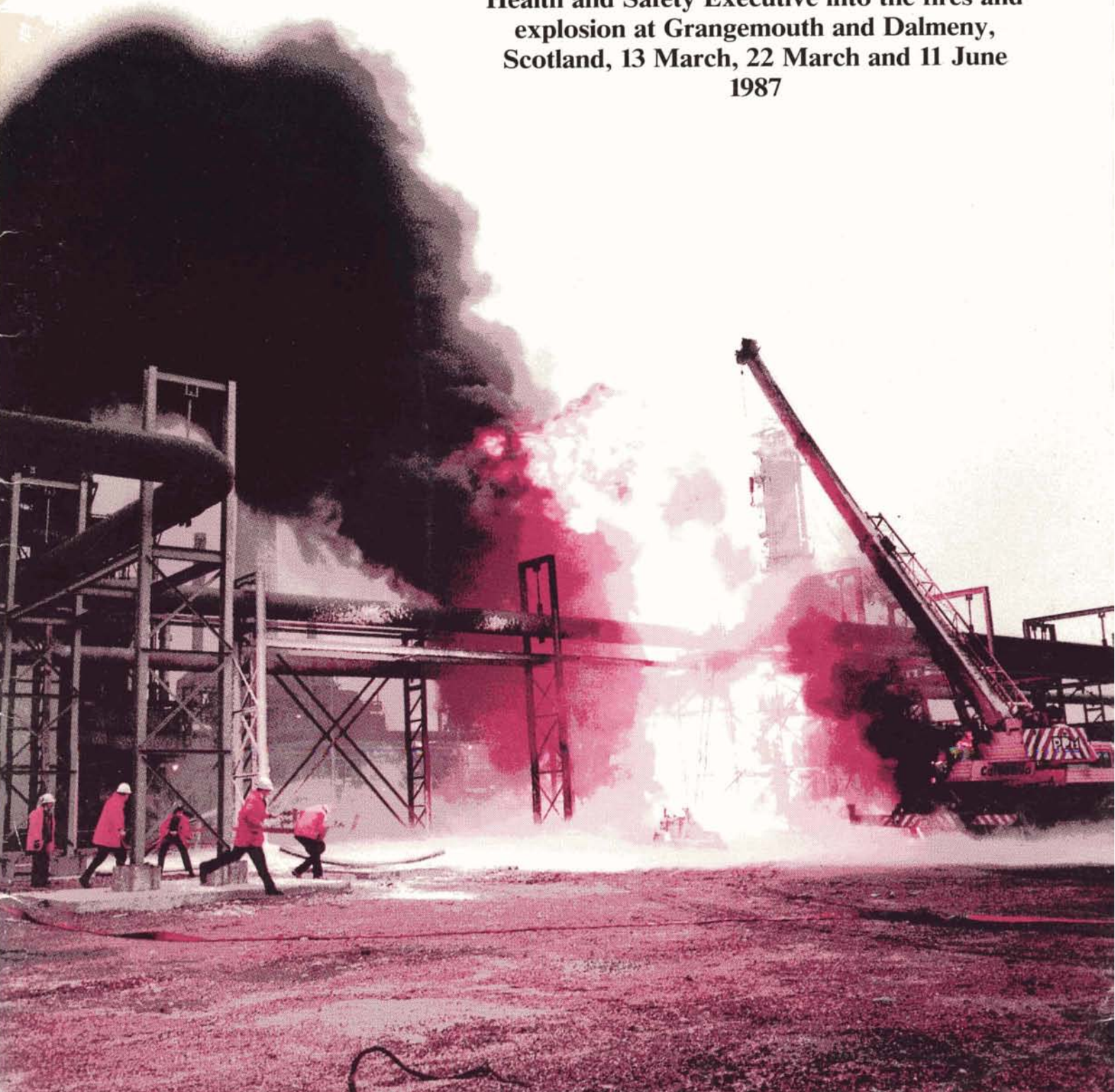


The fires and explosion at BP Oil (Grangemouth) Refinery Ltd

A report of the investigations by the
Health and Safety Executive into the fires and
explosion at Grangemouth and Dalmeny,
Scotland, 13 March, 22 March and 11 June
1987



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London: Her Majesty's Stationery Office

Introduction

1 This booklet describes the investigations made of three separate maintenance related incidents within a major British Company in 1987. The four deaths caused were all of contractors' men. The second incident, which invites comparison with the Flixborough disaster, could have had serious consequences for the public. The case studies here presented illustrate further the lessons drawn by the HSE publication *Dangerous Maintenance: A study of maintenance accidents in the Chemical Industry and how to prevent them* (Ref 1).

2 Firstly, a fire of flammable liquids, unexpectedly (although foreseeably) present and released during maintenance of a refinery flare system, killed two men and seriously injured two more. Potential ignition sources had not rigorously been excluded, means of escape were inadequate, and permit-to-work procedures had been devised and were being implemented without sufficient awareness of potential hazards.

3 Secondly, one man was killed and extensive damage was caused by a major explosion with consequent fire while the refinery hydrocracker plant was being recommissioned after repairs. Debris weighing several tonnes was propelled up to 1 km, in some instances off-site. Rupture of a vessel occurred following breakthrough of high pressure hydrogen, probably caused by less than perfect operating practices and made possible by the disconnection of safety devices.

4 Lastly, a fire within a storage tank at the refinery's crude oil terminal killed one of a contractor's team removing sludge. Smoking caused ignition. There had been persistent deliberate evasion of safety rules by some of that team - equally, those rules had not been effectively enforced by either the site occupier or the contractor.

5 Both refinery and terminal are subject to the Control of Industrial Major Hazard

Regulations 1984 (CIMAH). The process of producing and periodically reviewing safety reports should lead to the identification and elimination of deficiencies in plant and systems of work such as are illustrated by these case studies. HSE emphasise that safety reports for existing plant must reflect actual conditions and be based on appraisal of the plant as it is functioning at the time. A management view of how it should ideally be will not suffice - HSE hope that study of these incidents will demonstrate to companies undertaking hazardous operations the need for continuing self appraisal and constant vigilance.

Action taken

6 Following investigations into the incidents at the refinery, the HSE recommended to the Procurator Fiscal at Falkirk that two cases be taken against the operating company for breaches of Sections 2 and 3 of the Health and Safety at Work etc Act 1974. These were heard in the High Court in Edinburgh on 21 March 1988 when a fine of £250 000 was imposed for the charge relating to the circumstances of the flare line incident and £500 000 for the second charge arising out of the hydrocracker explosion.

7 The circumstances of the fire at Dalmeny were reported to the Procurator Fiscal at Edinburgh and a Fatal Accident Inquiry was held from 10-16 March 1988.

Description of the sites

8 BP Oil (Grangemouth) Refinery Ltd is part of BP Oil International. Their refinery site, situated on the outskirts of Grangemouth close to the River Forth, has been there since the early 1920s. Eight million tons of crude oil are processed per annum. There are 1200 full time employees and up to 1000 contractors may be employed on maintenance. Crude oil is received by pipeline from the ocean terminal at Finnart and from the North Sea Forties Field. End products, exported by road, rail, sea and pipeline, are kerosene, gas

oil, propane, butane, naphtha, motor spirit and fuel oil.

9 The oil storage terminal at Dalmeny near Edinburgh has the capacity to store up to 490 000 tonnes of stabilised crude oil prior to export by ship. Forties crude is piped 20 km to the terminal after being degassed at the refinery's Kinneil plant.

The Refinery Flare Line Incident: 13 March 1987

The flare line system

10 The flare line system comprising a complex of pipework which passes

through the refinery is shown in Fig 1. The dotted lines represent pipework which should have been isolated to enable the cross-over valve V17 (with which this incident is concerned) to be removed safely. Vented hydrocarbon gases from production units can be flared in three 91 m high flare stacks or recovered for fuel gas. Much of the flare system pipework is suspended on gantries about 4.6 m above ground. Sections can be isolated for maintenance by operating cross-over valves allowing vented gases from operating units to be re-routed. As gases pass through the extensive pipework system entrained liquids condense out on the unlagged cold surfaces.

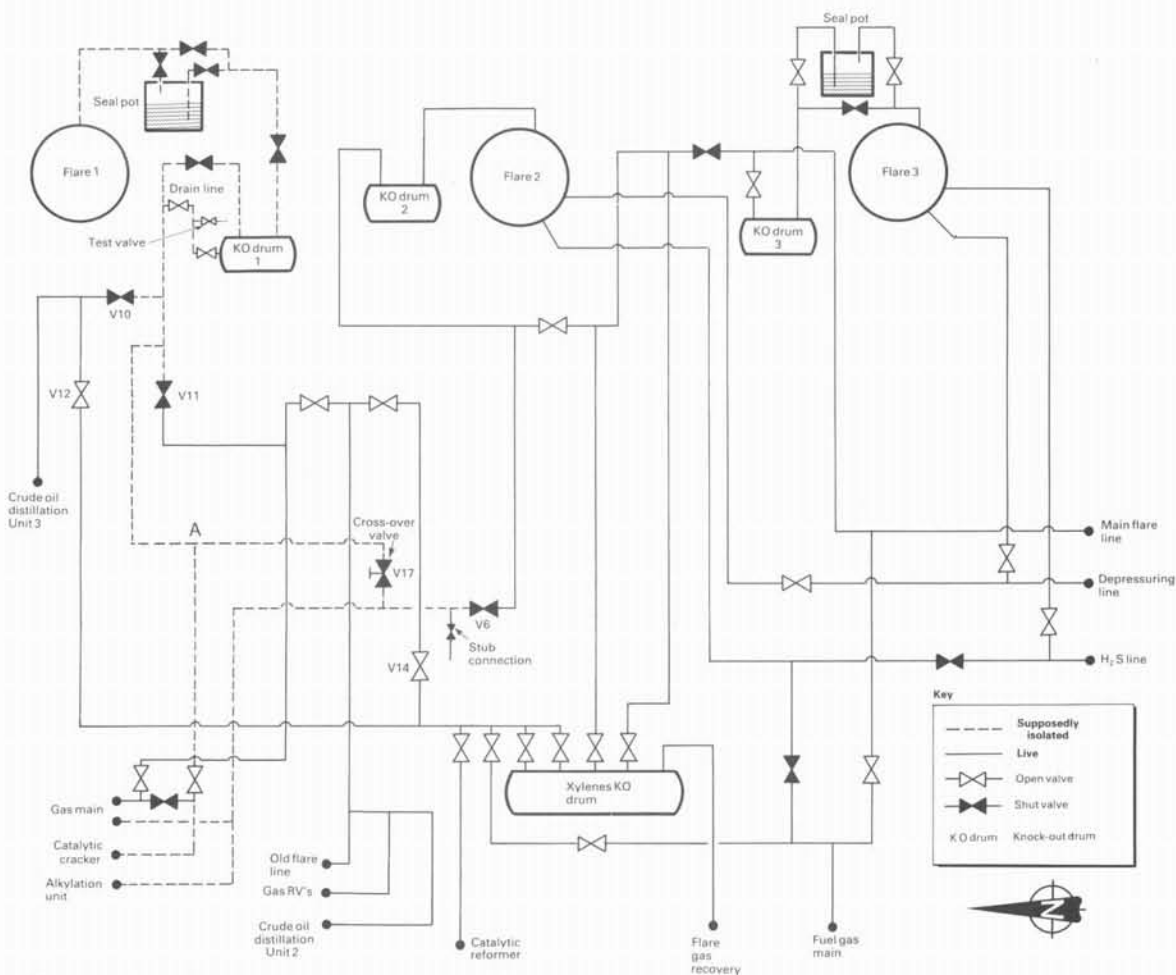


Fig 1 Refinery flare system

Photograph 1 Cross-over valve area on 14 March. Flare No 1 and knock-out drum No 1 in background. *Courtesy of British Petroleum*



Photograph 2 Cross-over valve V17. *Courtesy of British Petroleum*

11 Pipelines slope down to knock-out drums which collect the condensate for transfer to the refinery slops system for reclamation. At certain locations pipelines slope down in both directions, one such being at point A on Fig 1 which is 25 m to the north of V17. The 760 mm diameter lines slope down towards No 1 knock-out drum and down towards No 2 knock-out drum, via V17 and V6. The directions of slope are not marked and at gradients of 1 in 400 are not obvious. At V17 the direction of liquid flow could only be established by knowledge of the flare system or by survey.

12 Fig 2a shows a knock-out drum. As incoming gases and entrained liquids pass over the vertical loop into the upper part of the drum, the consequent loss of velocity causes liquids to separate out. Liquids already in the line by-pass the loop by means of a liquid take off. Gas is taken from the top of the drum to flare possibly via further knock-out drums, and the liquid which collects is pumped to the slops system.

13 Most of the flare system valves, including V17 consist simply of a movable wedge gate which can pass across the valve bore. An external gear wheel causes a threaded spindle to push the wedge gate into a guide to create a seal across the internal diameter. (Fig 3).

Events leading to the incident

14 Some 15 months earlier losses had been noted on the flare gas recovery system and gas from the alkylation unit normally routed to No 1 flare was passing to No 2. Tests showed that (although it appeared closed) V17 was not providing effective isolation and would require eventual removal for overhaul. It was decided that the loss of recoverable gas could be tolerated until a scheduled shutdown of the catalytic cracker, alkylation unit and No 1 flare. Gases from remaining operating units could be re-routed to No 2 and No 3 flares matching the maximum venting rates to the flaring capacity. This flare alignment would allow for the pipelines at V17 to be isolated.

15 About March 1986, senior refinery operations and engineering staff held discussions to preplan a scheme for the isolation of the flare system at V17. They concentrated on the operational and safety requirements of the refinery and the flare system. It was very important for safety reasons that the flare lines from operational units should not be inadvertently isolated. A system for flare alignment was drawn up. The procedures and safety precautions necessary for the removal of V17 were not considered. The detail was left to those who would eventually be responsible for the work.

16 In late January 1987 crude oil distillation unit 3 (COD3) was shut down for routine overhaul. In early February the operations department staff who were to oversee the removal of V17 held a meeting to discuss and agree the flare alignment outlined in Fig 1. Again the actual work methods were not considered, these being left to the two process supervisors responsible for general work activities on the flare system. About 22 February the catalytic cracker and alkylation units were shut down. The flare lines from each of these units were 'spaded' to provide effective isolation. Preparatory to its overhaul the No 1 flare was also isolated and 'spaded'. 'Spading' is a common refinery practice by which a section of pipe is positively isolated by the insertion of a blank flange. (Fig 4). On 9 March COD3 was ready to be started. Its line to flare No 1 was isolated by closing gate valve V10 and the operators had great difficulty turning the handwheel. Once they could turn it no further even using valve wheel keys with extension levers, they assumed it was closed and isolated although 75 mm to 100 mm of valve spindle protruded.

17 Two process supervisors were responsible for organising the work. Each had a team of process operators working to them in a double shift pattern. It was their job to isolate the appropriate part of the flare line system so that removal and repair of V17 could be carried out safely. The job of valve removal was put out to contractors.

Fig 2a Flare knock-out drum

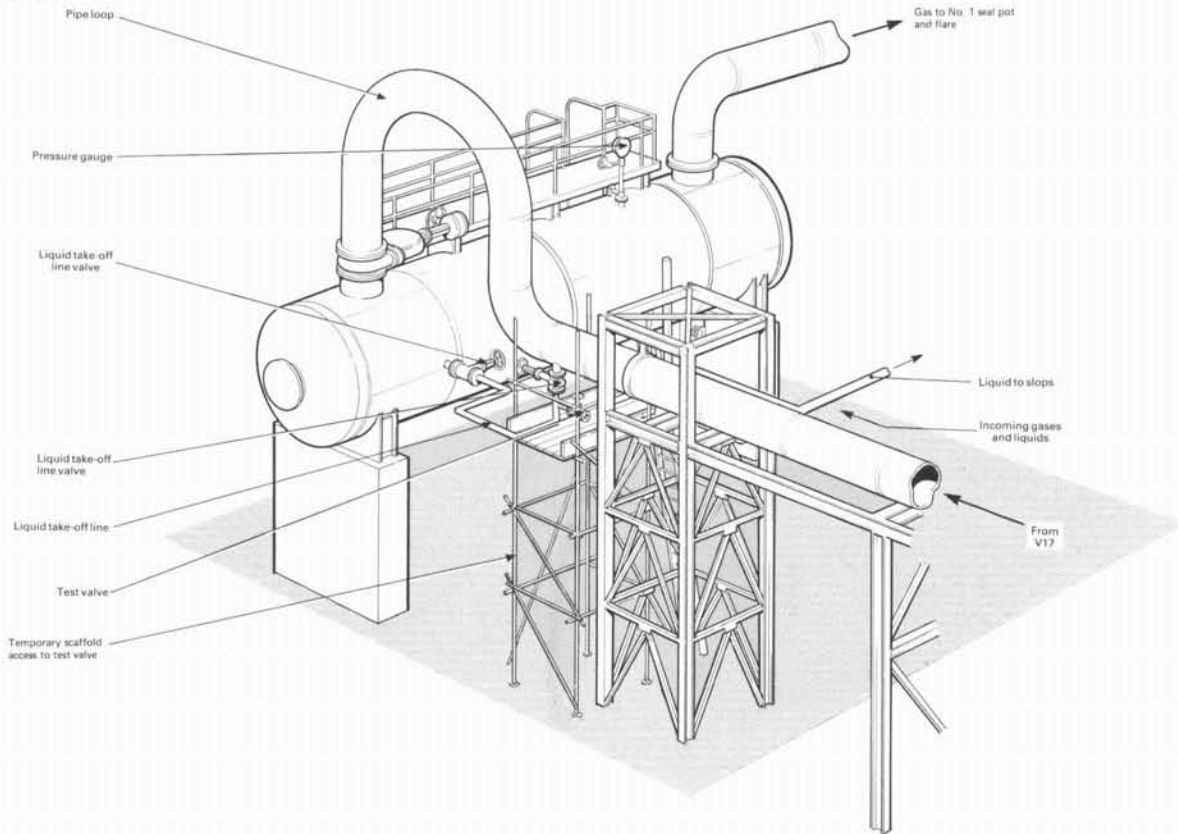
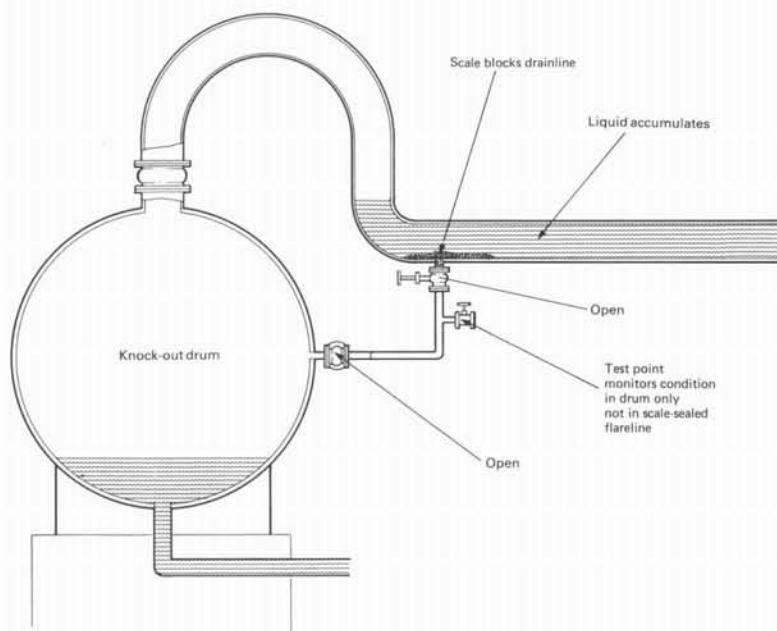


Fig 2b Effects of blocked liquid take-off line



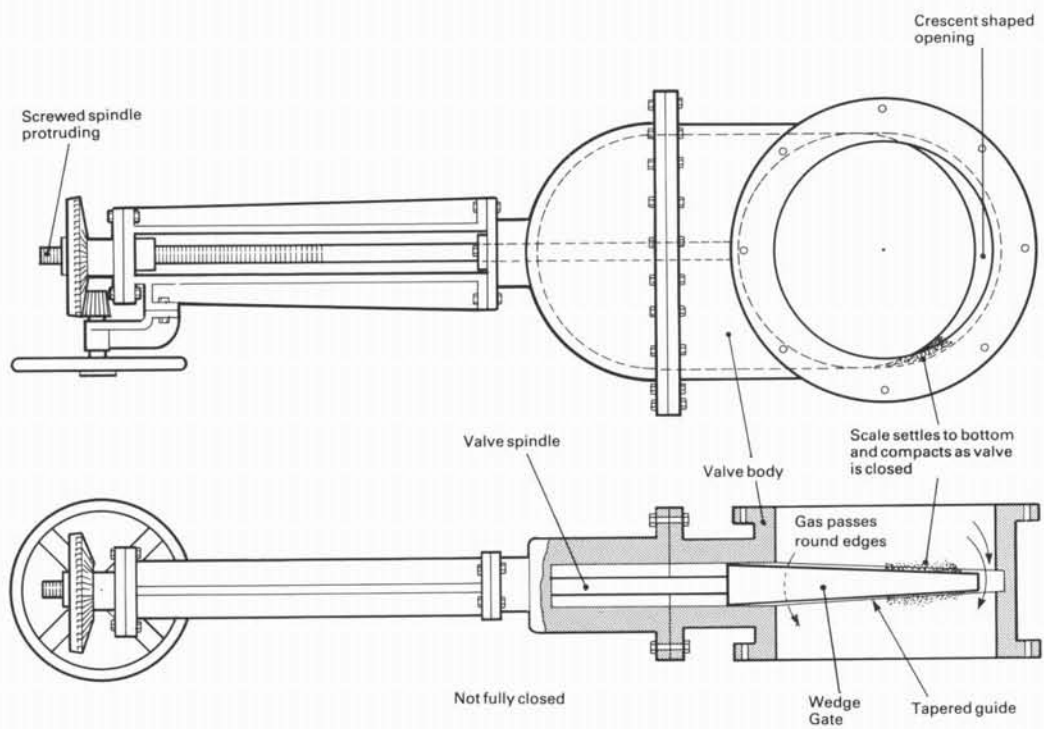
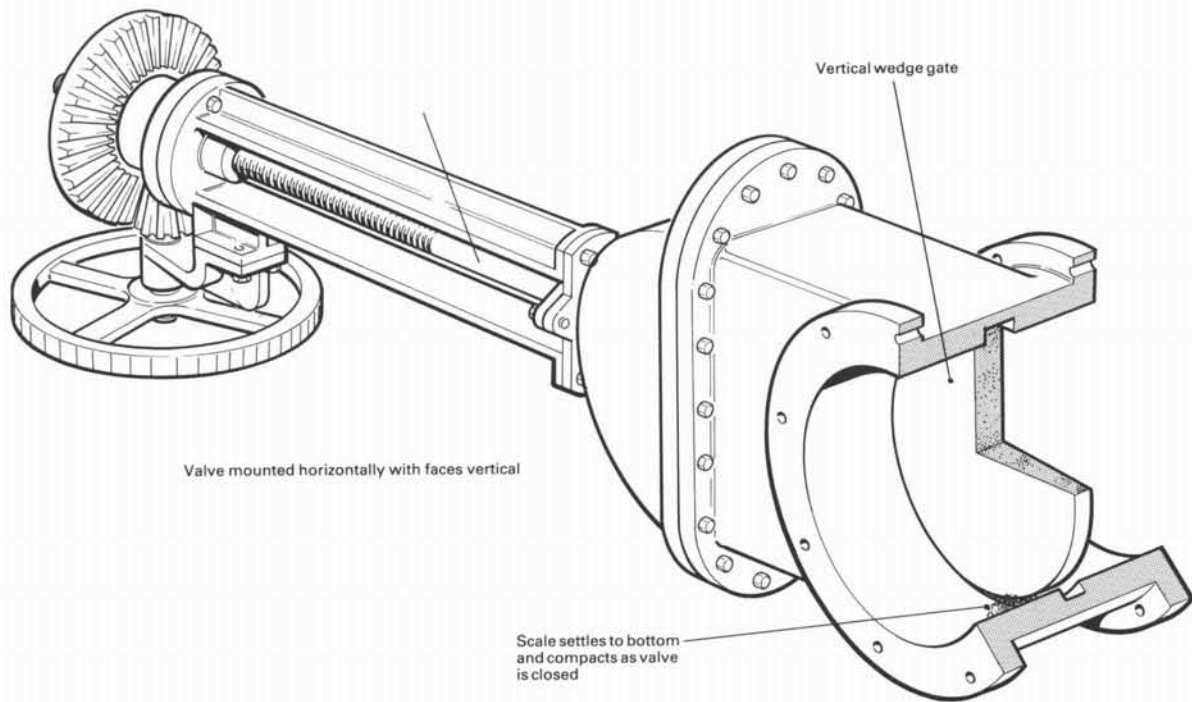


Fig 3 Flare line wedge gate valve

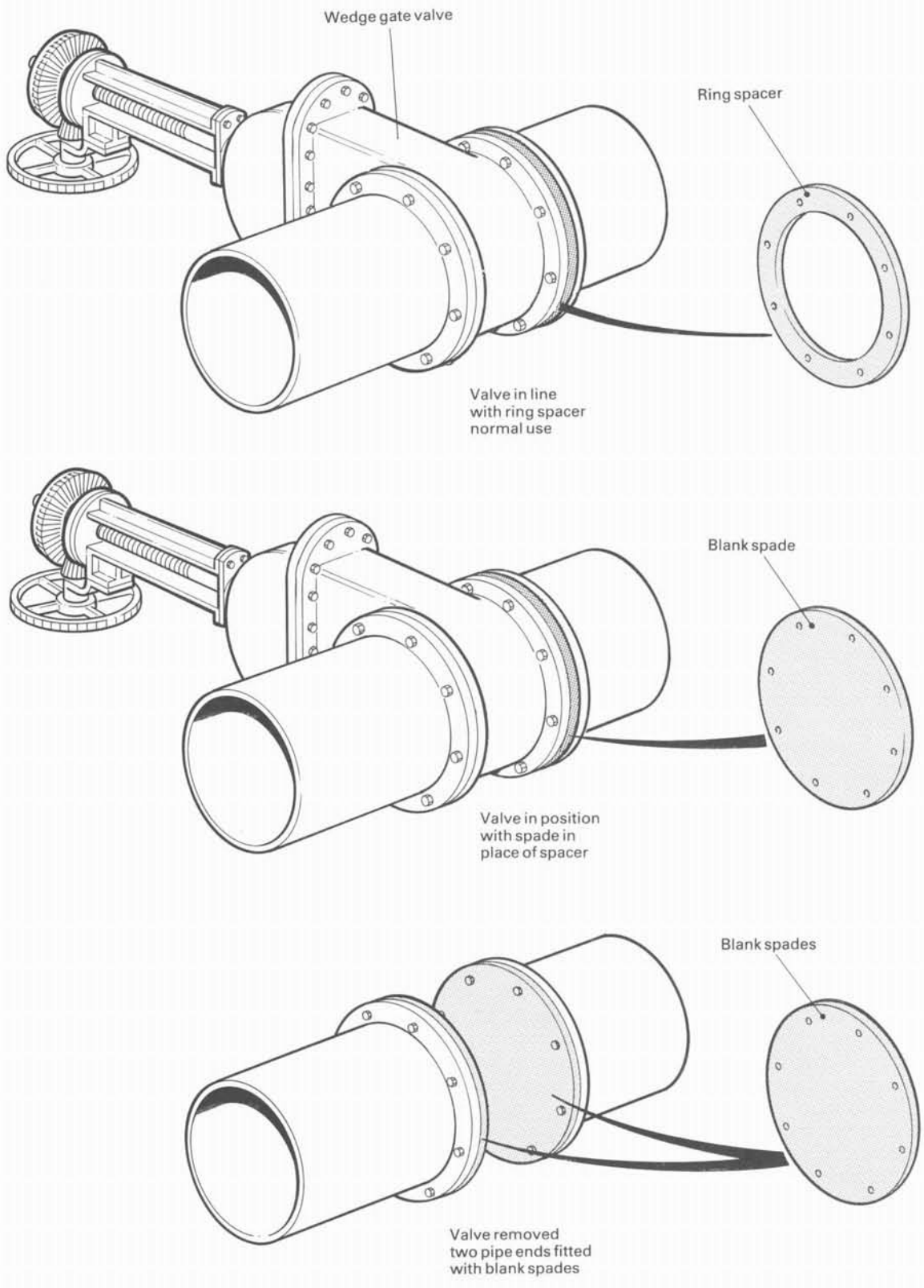


Fig 4 Flare line valve removal and spading

The permit to work

18 The refinery, following the general practice of the petroleum industry, controls potentially hazardous work by formal written procedures included in a permit-to-work. The permit, signed by a competent and 'authorised' person, usually a member of the refinery staff, should list the safety precautions which must be taken. Further guidance on permit-to-work procedures is contained in the Oil Industry Advisory Committee publication *A guide to the principles and operation of permit-to-work procedures as applied in the UK Petroleum Industry* (Ref 2). The 'authorised' official with oversight of the work in the course of issuing a permit intimates by his signature as the 'operating authority' that necessary safety checks have been properly done and that it is safe for work to commence subject to any special instructions indicated. On receipt, the form is signed by the 'performing authority', ie the person in charge of and responsible for those carrying out the work, who may be either a contractor or a BP employee. For removal of V17 a 'cold work' permit was drawn up as the work did not involve the application of burners or heat.

19 On the morning of 11 March, the contractor's shift superintendent as 'performing authority' sought a permit to enable preparatory work on V17 to be started. Alternate bolts on the flange joints were removed and the remaining bolts lubricated. This was standard practice to save time during the actual operation of valve removal. Sufficient bolts remained at all times to retain the flange seals. There was therefore at that time no need to verify line conditions. A permit was issued and the work completed without incident. A tower scaffold had been erected at V17 some months previously, the means of access to and egress from the working platform being a single ladder. The workmen, having climbed the ladder to the platform had to crawl under or over the valve body for work on the other side. This was to have serious consequences in limiting their avenues of escape.

20 The date for removal of V17 was finally set for 13 March and the work was discussed at the regular morning meeting between refinery staff and the contractor. The contractor's shift superintendent, the 'performing authority', approached the process supervisor on the early shift for a permit. Since the refinery compressed air distribution system did not extend to the work area, the supervisor made arrangements for a mobile diesel-engine air-compressor to supply the airline breathing apparatus to be worn by the men on the work platform. Respiratory protective equipment was necessary to protect them from the potentially toxic and asphyxiating effects of flammable residual gases which would escape from the flare-line when opened. Also, as a precaution against flammable gases being ignited, he arranged for two men from the refinery fire brigade to be present with a fire hose to form a water curtain between the work area and adjacent operating refinery units. These two precautions were subsequently written as special instructions on the issued permit (Fig 5).

21 Shift changeover occurred at 1315 hours and the incoming process shift supervisor was told by his colleague of the arrangements made. He was aware of the flare system isolation as he had supervised the work on earlier shifts. He was advised that the removal of V17 could commence after checks on flare-line isolation and line conditions and after the issue of a permit. He went to the cross-over valve area and confirmed that a fire curtain was available, that there was breathing apparatus and an air compressor, and that a crane was on site to lift V17 away. A slight wind was blowing towards the refinery and he requested a second fire curtain. He considered the compressor was too close and instructed it to be moved further away. The site layout around the work position was then as shown in Fig 6. He then checked line conditions by visual examination of the isolation valves. He was aware that they had been closed for many weeks and considered it necessary just to confirm that their status had not

COLD WORK PERMIT

Serial 0000

DATE AND TIME OF INITIAL 8 HOUR PERIOD	FROM 1500 13/3/87	TO 2200 13/3/87	WORK SITE N°3 COOL/PH
--	----------------------	--------------------	--------------------------

EQUIPMENT NAME/NUMBER: *Crude gas Valve between FCCU/Heb. Flow Bm*

DESCRIPTION OF WORK: *Removal of valve and install blank in place*

MARK	REQUIRED X	CHECKED ✓	YES	NO	Ch'kd	MARK	REQUIRED X	CHECKED ✓	YES	NO	Ch'kd
A. Has the equipment to be:-						C. Has the prime mover been:					
1. Depressured				X		1. Isolated from mechanical motive power and steam valves locked off?					
2. Drained			X			2. Isolated from other power sources?					
3. Isolated by - Blanking? Blank List No.				X		3. Electrically isolated, locked and tagged?					
- Disconnecting?				X							
- Valving?				X		D. 1. Has power cable been disconnected?					
4. Steamed?				X		2. Has control cable been disconnected?					
5. Waterflushed				X							
6. Purged with inert gas?				X		Authority granted to Isolate..... Time:.....hrs.					
7. Ventilated by natural/mechanical means?				X		OPERATING AUTHORITY					
8. Neutralised				X		Date:.....					
B. 1. Has worksite been passed for Excavation/stake driving to proceed?						Equipment Isolated..... Time:.....hrs.					
2. Has wind direction been considered?						ELECTRICAL SECTION					
3. Is a gas test required?						Date:.....					
4. Neutralising Solution on site?											
5. HF F/Aid kit available											

PROTECTIVE CLOTHING TO BE WORN: (Operating Authority) - (Indicate by 'X')

<input type="checkbox"/> FULL PROTECTIVE CLOTHING	<input type="checkbox"/> FACE SHIELD	<input type="checkbox"/> H ₂ S PRECAUTIONS	<input type="checkbox"/> T.E.L. CLOTHING	<input type="checkbox"/> ALKYLATION UNIT
<input type="checkbox"/> DUST MASK	<input checked="" type="checkbox"/> IR-LINE B.A.	<input checked="" type="checkbox"/> GOGGLES	<input type="checkbox"/> P.V.C. GLOVES	<input type="checkbox"/> ACID AREA CLOTHING
		<input checked="" type="checkbox"/> SELF CONTAINED	<input type="checkbox"/> EAR PROTECTION	<input type="checkbox"/> AIR FED HOOD
				<input type="checkbox"/> AIR FED SUIT

SPECIAL INSTRUCTIONS:-

** Filters air lines*

** Self contained BA - Piggors*

Fire Service to standby - water brought 4/1000

GAS TEST RESULTS	*COMBUSTIBLE/TOXIC/OXYGEN			*COMBUSTIBLE/TOXIC/OXYGEN		
	Date/Time	Result	Signature	Date/Time	Result	Signature
Initial Check -						
Re-check -						
Re-check -						

Site preparation is complete: - Permission is granted for work to commence.

To be signed by OPERATING AUTHORITY	Initial check	Date/Time	Re-check	Date/Time	Re-check	Date/Time
I am aware that this work is in progress and that conditions are as above.						
To be signed by OPERATOR IN CHARGE	Initial Check	Date/Time	Re-check	Date/Time	Re-check	Date/Time

PERFORMING AUTHORITY INSTRUCTIONS:-

I understand the precautions to be taken and have instructed the Person/ Persons carrying out the work accordingly. I will notify the Operating Authority when work is complete.

To be signed by PERFORMING AUTHORITY	Initial Check	Date/Time	Re-check	Date/Time	Re-check	Date/Time
--------------------------------------	---------------	-----------	----------	-----------	----------	-----------

Work completed at _____ hrs. on _____ (Date) Signed _____ Performing Authority

Electrical supply returned to equipment at _____ hrs. on _____ (Date) Signed _____ Electrical Section

PERFORMING AUTHORITY

Fig 5 Cold work permit

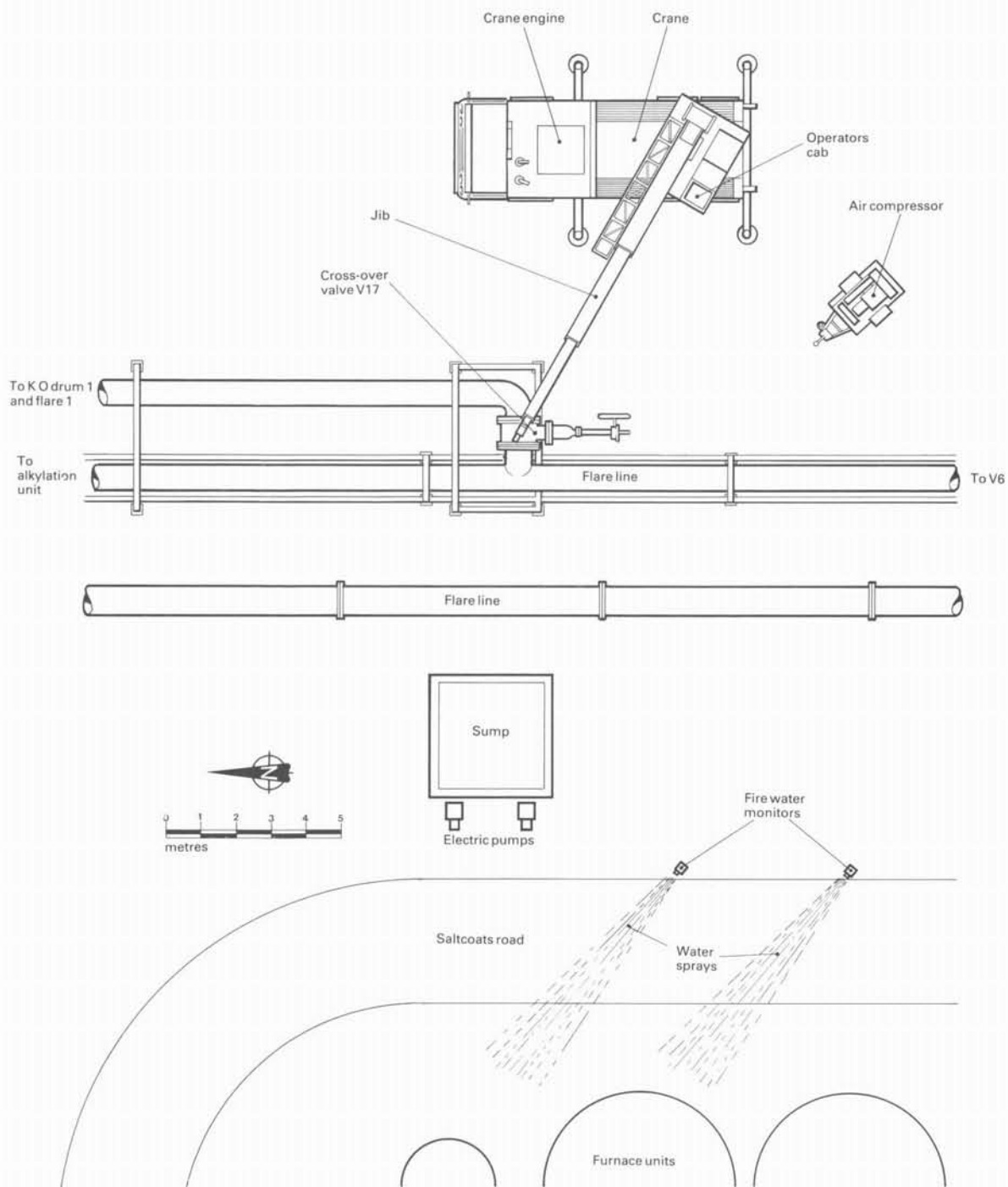


Fig 6 Diagrammatic representation of site layout

changed. There was no physical access to V6 which was thus only checked visually from ground level.

22 To check that there was no gas pressure in the line, the supervisor looked at the pressure gauge, scale 0-15 psig (0-1 bar) on No 1 knock-out drum. He assumed from the zero reading there was no gas pressure. He then opened a small valve on the 100 mm diameter drain line to the knock-out drum (Fig 2b) as both a second check on gas pressure and verification that the line was free of liquid. No liquid and only a small amount of gas passed out. He concluded that the flare-lines at No 1 knock-out drum and V17 were empty of liquid and had an acceptably low pressure of residual gas. The supervisor anticipated that valves on the system would not be completely leak tight when closed and that gas would pass into the isolated section. He believed he could accept some residual gas pressure because passage of gas out of the flareline when V17 was removed would help prevent ingress of air which could cause pyrophoric scale inside to ignite (para 31). Consequently the permit indicates that the equipment was not and did not have to be depressurised.

23 At 1500 hours the permit was issued. All concerned acknowledged that upon receipt the 'performing authority' was entitled to proceed on the basis that it was safe to start and continue.

The incident

24 Two fitters wearing airline breathing apparatus started to undo the remaining bolts on the spacer on the west flange. They were joined by a rigger wearing self-contained breathing apparatus, who secured a rope sling to a shackle on the spacer. When almost all of the bolts were undone the joint opened slightly and liquid dripped from the small gap between the flanges. Escaping gas and vapour could be seen passing out of the joint at the top. Being concerned about their safety in the presence of leaking flammable liquids and gases, they stopped work and came down from the

scaffold. They sought the advice of the 'authorised person', the process shift supervisor, who donned breathing apparatus and climbed up to the platform to check the situation. He saw gas issuing from the top and liquid leaking from the bottom of the flange. He concluded that neither was under pressure and that the quantity of liquid was small, being only that in the depression in the pipeline adjacent to V17. He carried out no further tests and assured the contractors that it was safe for work to continue.

25 The fitters remained concerned and, because they did not wish to create any potential sources of ignition by hammering at spanners or bolts, asked for and were given 'spark proof' (ie non-ferrous) hammers. Again wearing breathing apparatus, they returned to the scaffold. Liquid continued to drip as they removed more of the bolts. A refinery operator gave an instruction to take care when lifting the spacer and to lift it gently. The crane took the strain. At about 1610 hours as the last bolt was undone, the crane increased its lift and the spacer suddenly sprang upwards. In the words of a survivor "*gallons and gallons of liquid were coming from the pipe under pressure*" on to the platform and to the ground below.

26 A cloud of flammable vapour formed from the rapidly spreading pool of liquid on the ground. It ignited at the compressor and flashed back around the working area. One fitter and the crane driver managed to escape although they suffered burns. The rigger and the second fitter had been on the side of the valve remote from the ladder. Although they succeeded in reaching the ladder side of the scaffold they were engulfed in the fire. One body was subsequently recovered near the foot of the ladder and the other from the scaffold platform. Large quantities of liquid continued to escape and fuel the fire. The refinery fire brigade were quickly at the scene and were joined 10 minutes later by units of the Central Scotland Fire Brigade.

Investigation by HSE

27 The HSE was notified and inspectors responded immediately. When they arrived on site the incident was still in progress and the fire brigade were fighting the fire. For the first two hours the fire progressively diminished as the quantity of liquids in the flare-line decreased. However at 1800 hours, it again increased in intensity.

28 Investigation revealed that there had been some process difficulty with the stabiliser column condenser at COD3 resulting in gases venting to flare. As V10 was supposed to be closed, the vented gases should not have reached V17. It was thus apparent that V10 was passing gas and so probably were other isolation valves. Inspectors liaised with the emergency services and advised on the precautions necessary to enable safe recovery of the bodies. A major concern was that flare gas produced by refinery operations was feeding the fire. Inspectors met senior refinery management and engineers, and agreed with them that a controlled shut-down of much of the refinery was necessary, in order to ensure that no more gas could reach the incident point.

29 As the refinery shut down the fire diminished. There was concern that if the flame had been extinguished any subsequent gas escape could spread to cause an explosion. Additionally if the flame receded into the pipeline an internal explosion could result. Therefore refinery fuel gas was fed into the flare-line to keep the flame alight. By the next day conditions were safe enough to allow recovery of the body on the ground. The refinery obtained bulk supplies of liquid nitrogen and the inert gas was used to purge the system in order to extinguish the flame safely. This was successfully concluded at about 1300 hours on 15 March, and the second body was safely recovered from the scaffold platform.

30 A substantial amount of work was undertaken by refinery staff, who organised the removal of many large

valves, taking rigorous safety precautions. The valves were subjected to careful examination by HSE. On many of them pyrophoric scale, which is spontaneously combustible in air, was found to have compacted in the wedge guides. The effect of this is illustrated in Fig 3. Wedge gate valves can be closed through minor accumulations of scale or sludge, but eventually build up will prevent them from closing fully. They then no longer seal effectively and hence pipeline isolation may be prevented even though the valves are apparently closed. This problem is more likely to arise when valves are mounted horizontally with their wedge gates in the vertical position. V6, V10, V12 and V17 were installed in this manner. Flare line valves had nothing fitted to indicate whether or not they were fully closed and operators therefore assumed that they were closed when they could turn the handwheels no further even using wheel keys to give increased torque. In some cases, the screwed valve spindles protruded at least 150 mm, which was excessive. It is now recognised that sludge build up in V17 was the probable reason it allowed gas to pass.

31 Pyrophoric scale results from the interaction of sulphur-based gases and the mild steel commonly used for the majority of refinery vessels and pipework. The brittle scale builds up on internal surfaces of flare pipelines and breaks off as they thermally expand and contract in normal use. When mixed with liquid it forms sludge which can pass down lines and build up in valves. The danger of pyrophoric scale was referred to in the refinery operations department standing instructions and the pipeline section of their safety regulations.

32 The liquid drain line to No 1 knock-out drum was blocked, the effects of which are illustrated in Fig 2b. A blocked line results in the accumulation of liquid sufficient to prevent gas in the drum from registering line pressure. Therefore the test carried out by opening the small valve on the drain line to verify line pressure was ineffective and misleading.

Equally the absence of liquid from the test valve would not establish that the flare line was empty. The danger of small-diameter drain pipelines and valves quickly becoming blocked with scale and sludge, preventing the passage of gas and liquids, was well recognised and is referred to in the company's Code of Practice on piping systems.

33 Valve V6, to the south and slightly below the level of V17, had been closed for many months and condensate collected in the line. Close by V6 on the side leading up to V17, there was a 100 mm valved stub pipe which was installed as a test valve during flare-line construction and which could have been used as a drain and test point. The supervisor saw no need to test the line at this valve.

34 The quantity of liquid which was present in the system and the amount which escaped could not be determined accurately. The line before the expansion loop into No 1 knock-out drum was probably full and at V17 half full. HSE has estimated that the liquid inventory was 50 000 litres, of which 20 000 litres may have escaped. The severity and duration of the fire support these estimates.

35 The ignition source was almost certainly the engine of the diesel air compressor. Examination showed that the exhaust gas spark arrester was missing.

Preventive measures to avoid the incident

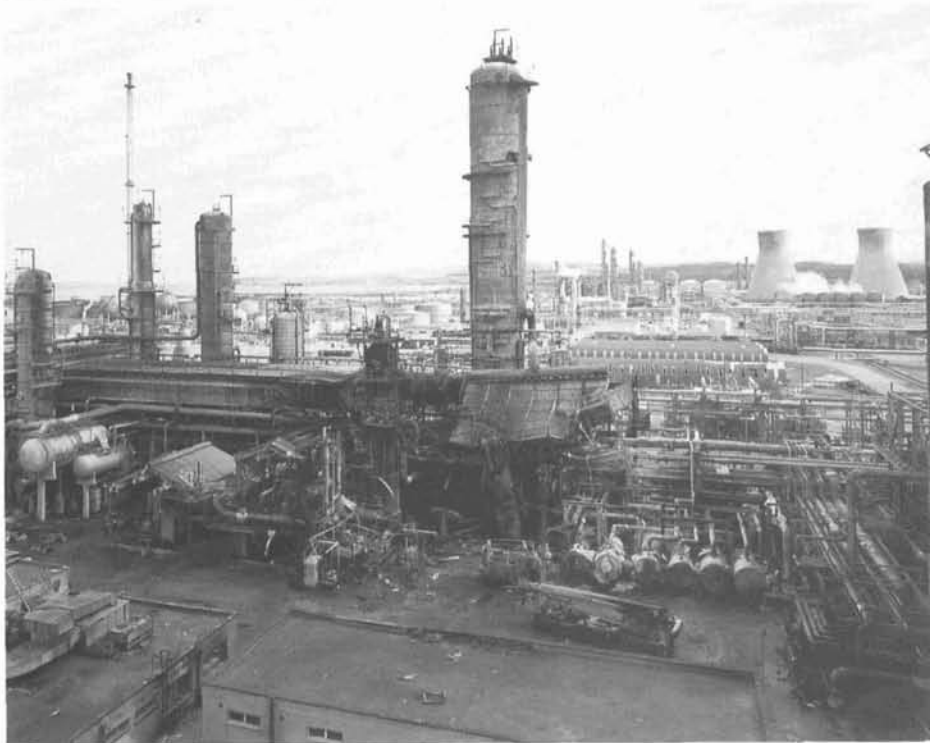
36 The following preventive measures should have been taken:

- (a) In order to ensure the effective isolation of the working area from other parts of the system, senior management should have carried out a more detailed analysis of the work and associated hazards. The detailed procedures involved in isolation and effective drainage of hydrocarbon liquids from the flare-lines at V17 should have been agreed at that level before being delegated.
- (b) Knowing the risk that sludge and scale can prevent gate valves from closing, checks should have been required to ensure that all relevant isolation valves were fully closed. An internal 1983 engineering code of practice which was concerned with the safety of flare-line operations stated: "*flare-line isolation valves should also incorporate valve position indicators*". The refinery did not consider this code to be retrospective nor did they consider it related to work activities. Valve position indicators would have assisted the isolation and since the accident they have been fitted.
- (c) The drainage and line contents should have been checked at two points at least. The possibility of small-bore pipes being blocked should have been considered and checks made. The clearance of test and drain lines could have been verified by the passage of steam or nitrogen.
- (d) Means of access to V6 should have been provided and the valve opened so that liquid build up could drain away. After closing the valve, checks on line contents should have been made using the conveniently located valved stub connection, itself verified as free of blockage as outlined in (c) above.
- (e) When work on V17 stopped as liquid came from the open flange, line contents should have been established by further checks on isolation and drainage. Work should not have restarted until there was absolutely no doubt over line conditions and the safety precautions necessary.
- (f) There should have been detailed safety instructions for the opening of any pipeline which could contain residual quantities of flammable liquids or gases, including a requirement for sufficient bolts to remain while a gradual opening is made by the use of a flange spreader,

for example. Drip trays could collect leakage in a controlled manner.

- (g) Adequate means of escape in case of an emergency should have been provided from the elevated working platform. In this instance a single ladder was insufficient.
- (h) Rigorous control should be exercised over possible ignition sources in the vicinity of such operations. There should be a system for checking all equipment used on maintenance.
- (j) When it is necessary to open pipe systems which may contain pyrophoric scale, reliance should not be placed on the presence of residual flammable gas to exclude air. Nitrogen purging should be considered but this can cause pyrophoric scale to dry out so increasing danger from spontaneous combustion, if it is subsequently exposed to air. Because of the complexity and hazards associated with such operations there is no single set of measures which will ensure safety and this highlights the need for each job to be pre-planned at a senior level. After the incident the refinery successfully removed many large flare-line valves. Nitrogen purging was used. In addition to the above precautions the men working on elevated platforms wore fire suits and they were withdrawn to a safe distance before opening lines. The disconnected and supported spacers and valves were lifted out by crane during which the whole area was drenched with water sprayed from fire hoses, which both wetted any pyrophoric scale and dissipated escaping residual gas. The drenches then remained until protected employees had fitted spades to the open pipe ends.

The Hydrocracker Explosion and Fire: 22 March 1987



Photograph 3
Hydrocracker area looking east

The hydrocracker unit

37 'Hydrocracking' describes an exothermic refinery process involving the break down of low grade waxy products and thick viscous oils by subjecting them to hydrogen gas at high temperatures and pressures in the presence of a catalyst to form high grade light oils, petroleum spirits and liquid petroleum gas (LPG). Fig 7 shows a simplified representation of the hydrocracker process flow system.

38 The hydrocracker unit at the refinery consisted of a series of 4 fixed bed vertical reactors, operating in an atmosphere of hydrogen at 155 bar (2250 psig) and 350°C. Waxy distillates were continuously fed through the reactors from a feed surge drum at a maximum rate of approximately 32 000 barrels/day (b/day) (3500 litre/min). The

temperatures of the reactor beds were monitored and at 425° temperature cut outs (TCOs) would operate to stop the input of wax feed and hydrogen. Sequenced depressurisation of the system would start through blow down valves into the flare system. Hydrogen recycle would continue through the reactors to assist cooling during depressurisation. Hydrogen make up feed gas for the reactors came mainly from a hydrogen production unit augmented by a supply which was a by-product from the catalytic reformer. The gas composition was subject to minor variations according to its methane content.

39 From the reactors the hydrogenated liquid/gas mixture passed forward through a series of heat exchangers and a fin fan cooler into a vertical high pressure

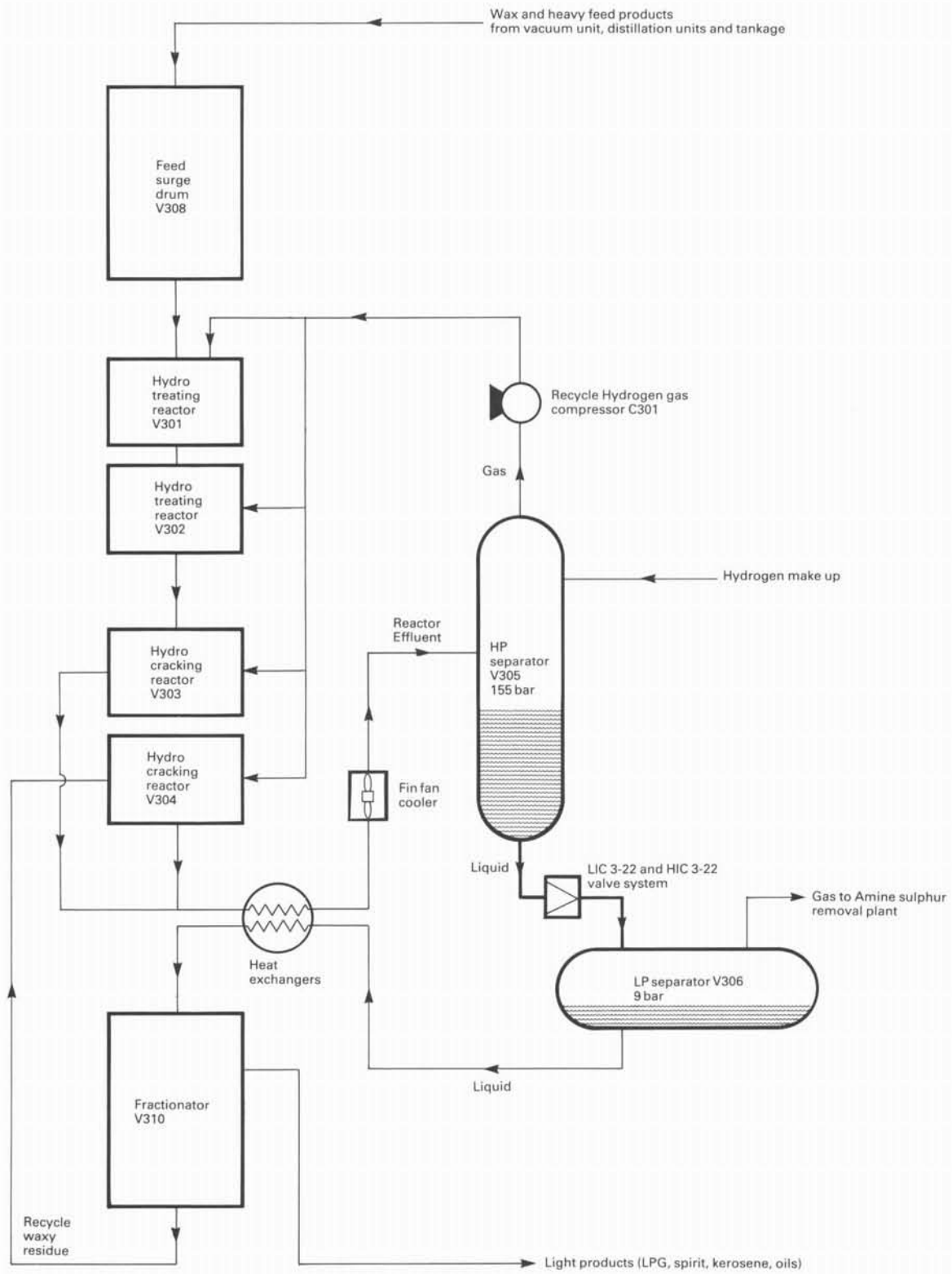


Fig 7 Hydrocracker process flow system

separator (V305) at a temperature of about 50°C. In V305 the hydrogen and light gases were separated from the liquid and passed to the inlet of centrifugal compressor C301 to be recycled to the reactors. This compressor vibrated at high differential pressures and although it gave reliable service, it was crucial to the operation of the plant. Thus vibration was closely monitored to prevent breakdown. From V305 the liquor at 155 bar and 50°C was then passed via control valves to a horizontal low pressure separator (V306) where more hydrogen and light hydrocarbon gases separated from the liquor as the pressure dropped to about 9 bar (135psig).

40 The de-gassed liquor from V306 then passed through heat exchangers into the fractionation unit where products such as kerosene, gasoline, naphtha and petroleum gases were separated from the uncracked residue. The conversion efficiency of the hydrocracking process was typically 60%. Unconverted liquor was recycled for further hydrocracking. At 32 000 b/day throughput and 60% conversion, the maximum flow of liquid from V305 to V306 was about 5900 litre/min, consisting of 3500 litre/min feed and 2400 litre/min recycled residue. Gases from V306 passed to the amine treatment plant to remove sulphur.

Table 1 Typical HP and LP separator operating parameters

Parameters	HP separator (V305)	LP separator (V306)
Length	15.6 metres	9.1 metres
Diameter	3.05 metres	3.05 metres
Liquid Volume	33 000 litres	33 000 litres
Vapour Volume	79 000 litres	33 000 litres
Temperature	41°C	43°C
Pressure	155 bar	9 bar
Liquid specific gravity	0.85	0.85
Vapour molecular weight	5	15
Weight of liquid	27.7 te	28 te
Weight of vapour	2.1 te	0.2 te
Weight of hydrogen	0.8 te	0.04 te

41 The process was operated locally from a plant control room, situated some 37 m from V306. A plot plan of the area is shown in Fig 8.

Events leading to the incident

42 On 13 March the hydrocracker unit was taken out of service to carry out essential repairs. Late on Saturday 21 March it was being recommissioned. At the start of the nightshift at 2200 hours, production was steady at 20 000 b/day. At about 0130 hours on Sunday alarms sounded in the control room. The plant tripped and a number of pumps and compressors shut down automatically; feed to the reactors was interrupted and the system started to depressurise. It was noted that one of the TCOs on V303 had caused the plant trip.

43 The hydrocracker appeared satisfactory and the TCO was thought to be spurious. No over temperature condition was found and the TCO trip was overridden enabling hydrogen circulation to be re-established. The instrument section verified the reactor temperature control circuits confirming that they were working. At about 0200 hours the night shift operators started to bring the plant up to working pressure and to stabilise reactor bed temperatures preparatory to start up. From then until the time of the incident, the plant was being held on standby with no feed coming through. There was nothing of special note in the operation except for a slightly higher than usual vibration from C301.

44 In accordance with instructions operators delayed introducing feedstock until the arrival on site of the hydrocracker supervisor. At 0600 hours the shift changed. The day shift was told the plant had shut down because of an unexplained TCO, that there was excess vibration on C301 compressor and that the plant was to be kept on standby pending the arrival of the supervisor. Between 0645 and 0655 the majority of operators returned to have breakfast in the mess-room within the control room building.

The explosion and fire

45 At 0700 hours there was a violent explosion followed by an intense fire. The

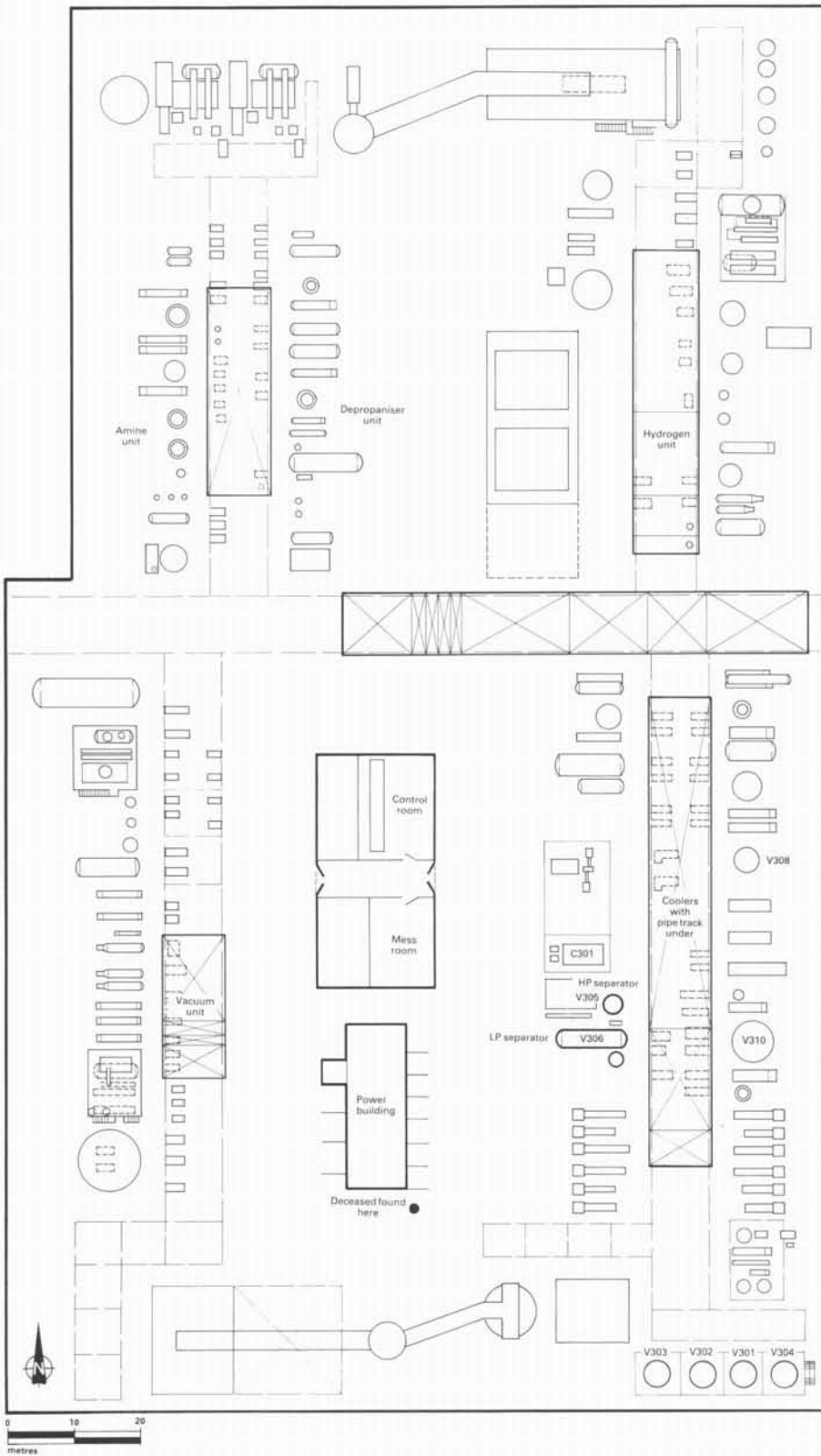


Fig 8 Plan of hydrocracker complex

explosion was heard and felt 30 km away and it caused considerable local concern. A contractor who had just left the mess-room was killed. The explosion centred on V306 which was constructed from 18 mm steel plate and weighed 20 tonnes. Photograph 4 shows the hydrocracker area with two T-shaped plinths on which V306 stood to the left of centre. The vertical HP separator (V305) is on the far left. V306 had disintegrated and large fragments were projected considerable distances. A piece weighing nearly 3 tonnes was found on the foreshore 1 km away. Another was projected over a main road into a factory where it severed a steam line. A third went through the roof of a workshop on an adjacent site. During the investigation almost all of V306 was recovered and the positions where the main fragments landed are shown in Fig 9.

46 At the time of the explosion there were nine operators within the hydrocracker complex. Two were in the control room; six were in the adjacent mess room having breakfast; the ninth was out on the plant. Although the control room and mess room building of conventional brick construction suffered considerable damage, it remained standing. Those inside were uninjured and escaped by the rear exit. The operator outside was far enough away and escaped the worst effects of the blast. The only other person in the vicinity was the contractor.

47 The Grangemouth Major Incident Plan was put into operation and its Control Committee comprising representatives of the Police, Fire Brigade, District and Regional Councils, and experts from the refinery and from major chemical and petroleum companies in the Grangemouth area, co-ordinated the provision of emergency services and the response to off-site events. The incident on-site was dealt with by the Police and Fire Brigade, assisted by refinery staff. Twelve units of the Central Scotland Fire Brigade and the refinery fire brigade fought the fire. Supplies of foam were provided by BP and brought in under a

mutual aid arrangement from other localities throughout Scotland under the refinery's emergency plans. HSE inspectors were in early attendance.

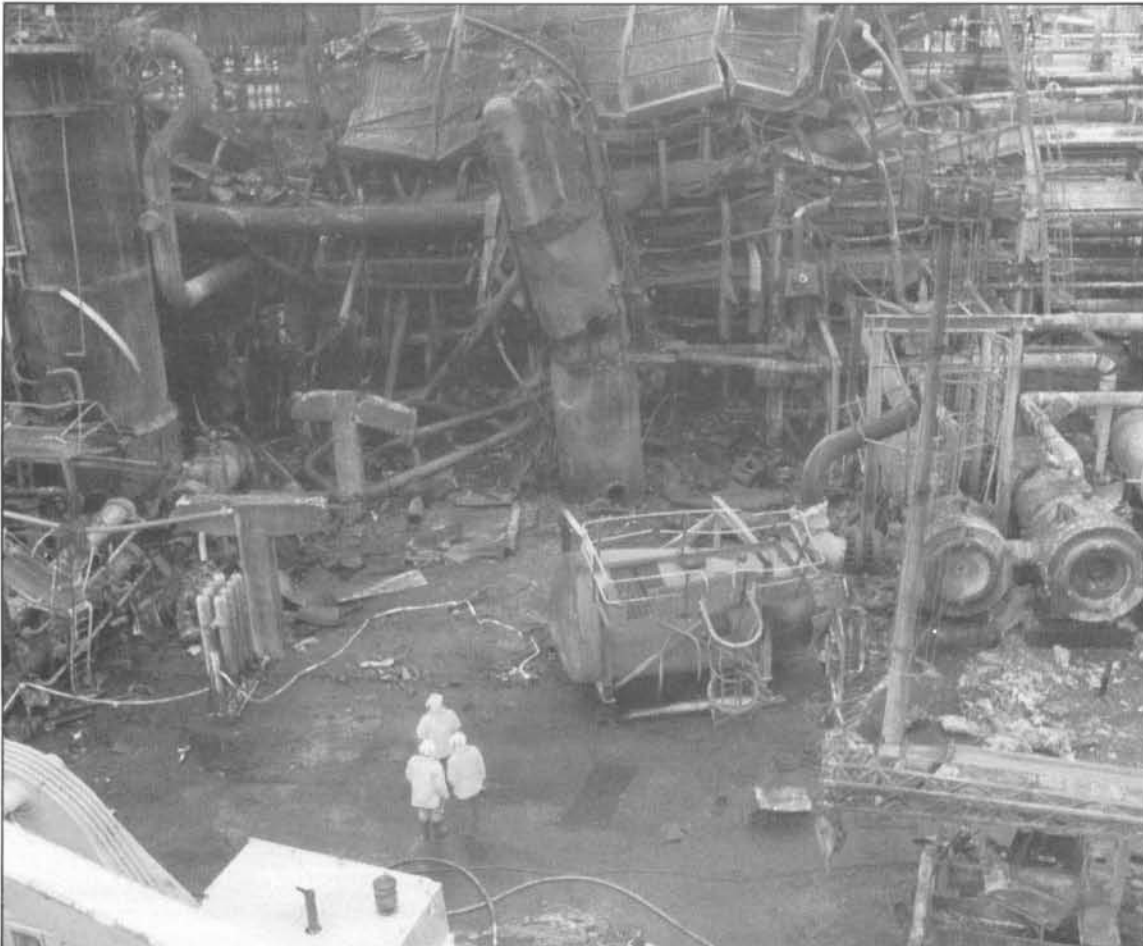
48 Difficulties in fighting the fire arose because waxy material from ruptured pipework blocked drains causing fire water to accumulate. Leaking petroleum spirit spread over a large area of the resultant water surface and five hours after the explosion it ignited. A number of other process units in the hydrocracker complex were enveloped in flames. Fortunately, the fire brigade were able to regain control and that evening the fire was finally extinguished.

49 The potential consequences of the incident could have been much greater. It occurred on a Sunday morning when few people were on site. V306 ruptured at support saddles underneath the vessel and the blast force was directed downwards with fragments being projected upwards. Had it been otherwise, the control and mess room building could have been destroyed, increasing the likelihood of death and injury. Fortunately none of the fragments hit vulnerable plant nor did they strike anyone. The risk did not warrant evacuating local residents but non essential personnel left the site. As a precaution traffic on the adjacent road was diverted.

Investigation by HSE

50 Initial fire and explosion evidence suggested there had been an explosive pressure vessel failure involving V306 followed by release of the gas and liquid contents as a cloud or mist. This produced not only a fireball but also blast effects due to the semi-confined nature of the plant. There were a number of possibilities which could have lead to such a failure including:

- (a) an external event, such as sabotage or an incident on adjacent plant.
- (b) internal explosion.
- (c) mechanical failure under normal operating conditions arising out of a critical defect within the vessel or



Photograph 4 LP separator support plinths

through other effects such as vibration.

(d) accidental overpressurisation.

51 The investigation involved:

(a) Recovery and metallurgical examination of vessel fragments on which ballistic calculations were based.

(b) Recovery and examination of fire damaged components.

(c) Examination of control room instruments and records.

(d) Interviewing operating and management staff.

52 With respect to (c) and (d), HSE were alerted by the refinery management that there had been alteration of some instrument settings before security was fully established around the accident location. The accounts given by some operators did not and still do not tally with the physical evidence. It was not possible to establish unequivocally from the operators' evidence the sequence of events which resulted in the explosion. The investigation therefore attempted to reconstruct the physical conditions necessary to account for the incident.

53 The normal operating pressure for V306 was 9 bar (135 psig), its design

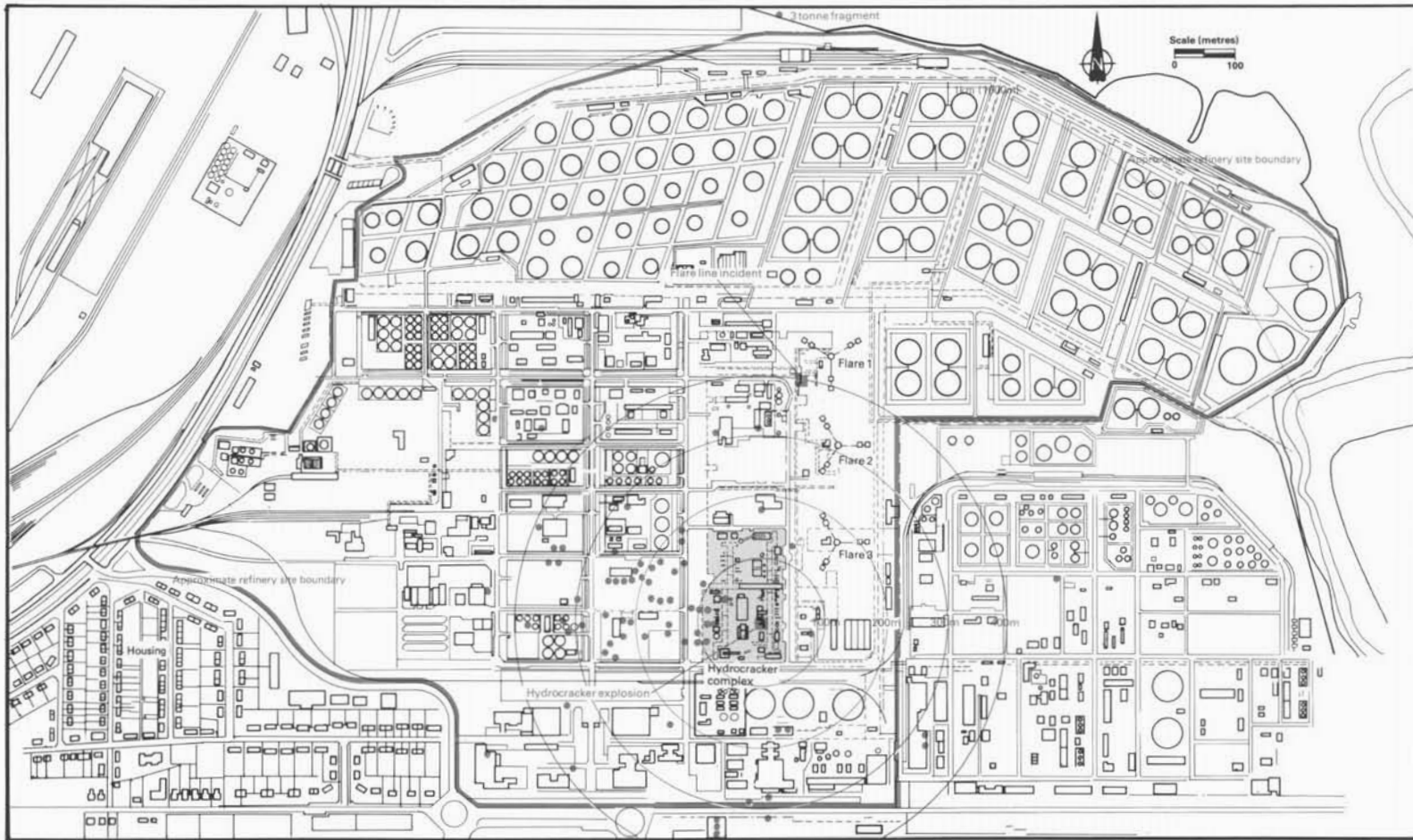


Fig 9 Refinery plan showing location of hydrocracker explosion and debris, and location of flare line incident



Photograph 5 Fragment from LP separator; distance 340 metres



Photograph 6 LP separator end section projected 75 metres over control room building

pressure 10.7 bar (160 psig) and its test pressure 21.6 bar (324 psig). It had a single pressure relief valve with an orifice area of 18 cm² and a relief capacity to flare of 12.25 tonne/hour, sufficient to cater for overpressure from fire engulfment. There was no evidence to suggest that this relief valve was not operating effectively at its set pressure of 10.7 bar (160 psig).

54 The fragments of V306 were located, weighed and their positions logged. The explosive forces were calculated using ballistic techniques based on fragment trajectories which confirmed that rupture was caused by over-pressurisation. The results correlated well with the calculated theoretical burst pressure of 50 bar (750 psig). Blast damage established that the force of the explosion was equivalent to approximately 90 kg of TNT.

55 The overwhelming weight of evidence from blast damage, ballistics and metallurgical examination pointed towards internal overpressure of V306 applied in a single event. Nevertheless other possibilities of vessel failure, as set out in para 50, were also considered by detailed examination of the plant, plant records and eye witness accounts. There was no indication of an external initiating event such as sabotage. An internal explosion or ignition occurring within V306 was considered. This would have required the presence in the vessel system of both oxygen and a source of ignition, and the possibility was eliminated not only by detailed consideration of the process conditions and controls, but also by evidence from vessel fragments.

56 The possibility of mechanical failure for reasons other than simple overpressure was considered. The metallurgical evidence established that the origin of the failure was in the heat affected zone of a saddle weld on the underside of the vessel at the east end near the support plinth. There was no indication of pre-existing defects nor of a progressive mode of failure on any part of the fracture surface examined. Cracks

had grown rapidly from the origin in two opposite directions, in a predominantly brittle manner, consistent with fracture under high strain rate conditions at a temperature near the impact transition temperature of the material in this thickness. On a plant of this type it is foreseeable that fluid transfer could set up vibration effects giving rise to high transient strain rates. At operating temperatures well below normal a vessel subjected to these vibration effects could have failed.

57 However the other evidence strongly suggested that there had been a breakthrough of high pressure gas from V305 to V306 leading to overpressurisation of the vessel. The liquid in V305 had drained away through an output flow control valve when the hydrocracker was being held on standby operation with no product passing, thereby allowing high pressure gas to break through. Fig 10 shows a single 300 mm diameter outlet pipe from the bottom of V305 which split into two parallel streams each with a separate flow control valve. The valve nearest V305 was the right-angled, air-diaphragm-operated valve LIC 3-22 which could be operated from the control room either in automatic or manual mode. Some distance from V305 was the air-diaphragm-operated, straight-through flow control valve HIC 3-22, which could only be operated via a manually applied control signal from the control room.

58 Fig 11 shows the LIC 3-22 and HIC 3-22 valve control system. A pneumatic diaphragm assembly opened each valve. On removal of air pressure the valve was closed by a spring. Its position was selected by a control unit from which an electrical signal passed to an I/P (electrical current/air pressure) converter. A pneumatic signal was then sent to a positioner unit at the valve. By this means air pressure was applied to the diaphragm. Two hand-wheel-operated valves (SP25) in series provided a manual by-pass to the control valves. One was found open but the other was shut and found to be gas tight. Gas breakthrough,

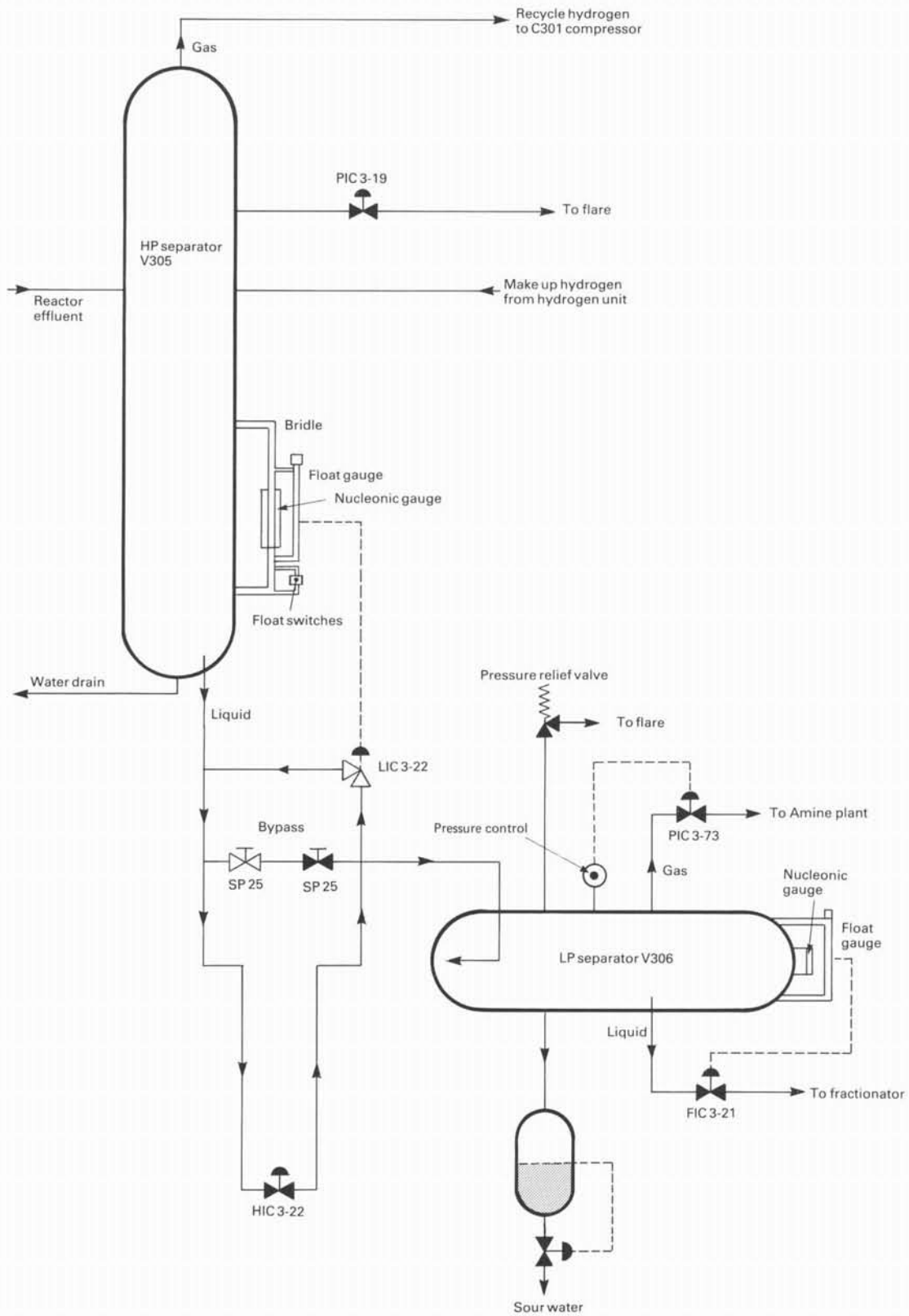


Fig 10 HP/LP separator control system

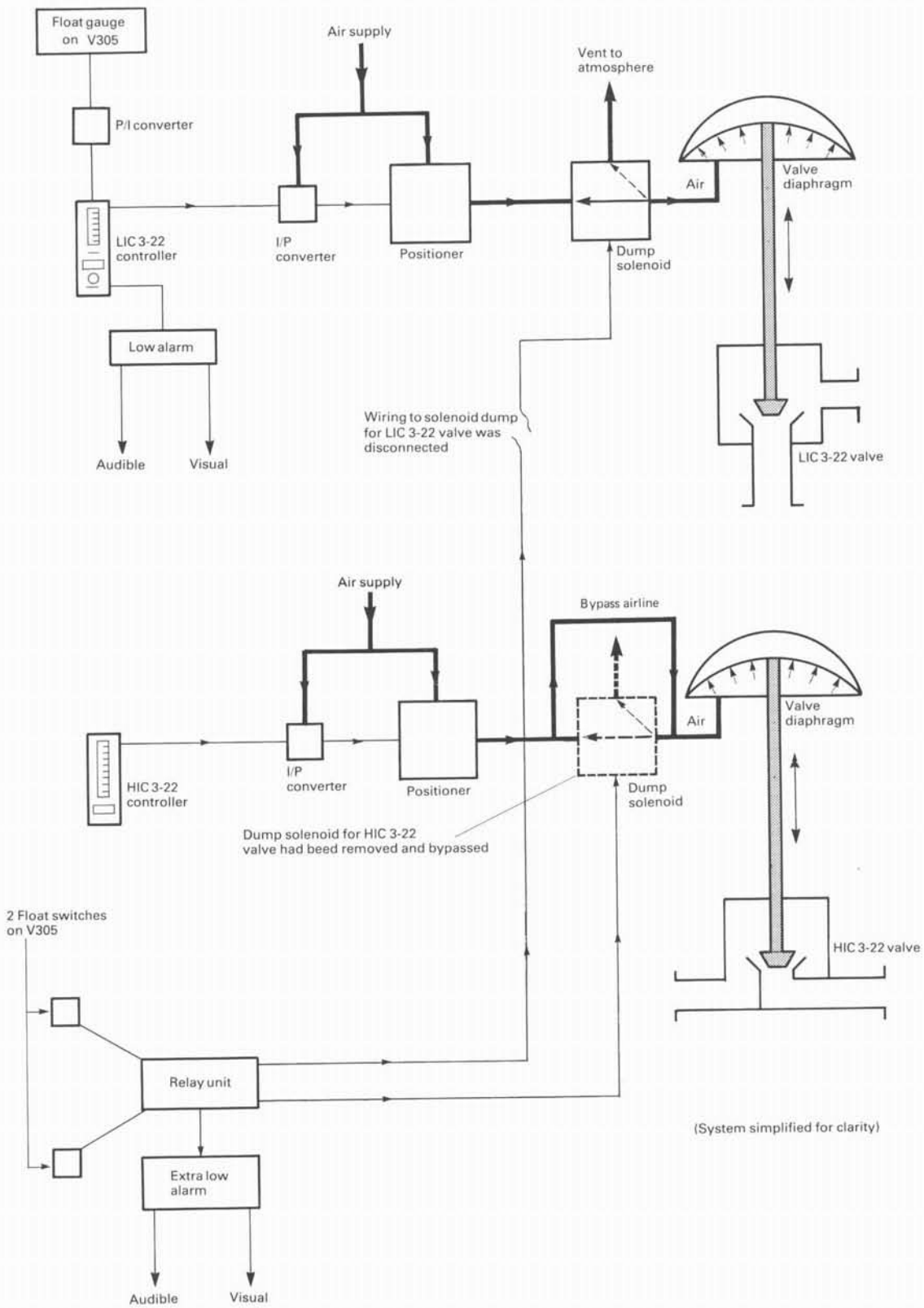


Fig 11 LIC 3-22 & HIC 3-22 valve control system

therefore, did not occur through the bypass route.

59 HSE tested the HIC 3-22 and LIC 3-22 valves. Apart from fire damage to the diaphragm assembly and positioner on LIC 3-22, they were found to be in working order and sealing reasonably effectively when in their closed positions. When valves were removed, waxy material was found in all except LIC 3-22 evidence that gas had passed through it purging it of wax.

60 The possibility that a valve positioner fault could have caused a valve to open was considered. The positioner on HIC 3-22 was working but that on LIC 3-22 was destroyed. Fault conditions were simulated on an identical positioner which showed that in the event of a component failure a valve would close rather than open. Positioner failure leading to LIC 3-22 opening was thus discounted.

61 The liquid level in V305 was measured by a 3.6 m long tubular float gauge, and a nucleonic level sensing gauge both attached to a pipework bridle. Levels were shown in the control room on indicators and chart recorders. V305 contained 11 500 litres or less when the float gauge registered 0%. A 1% variation in the float gauge reading was equivalent to 266 litres, and at a 50% reading V305 thus contained 24 800 litres. Signals from the float gauge also provided input to the LIC 3-22 controller (shown in photo 8) to provide level indication and to control the opening of LIC 3-22 to a level set by the operator with the controller set to automatic. The LIC 3-22 and HIC 3-22 controllers were tested and found to be in working order and correctly calibrated.

62 If the level in V305 fell to 20% (16 800 litres) on the float gauge, signals triggered a 'low liquid level' audible alarm and a warning light showed on the control panel to alert the operator, so that he could monitor it or take corrective action. Operators could 'accept' the alarm by pressing an 'acknowledge' button

which stopped the audible alarm and made the flashing light steady until the alarm condition was cleared on plant. The low level alarm was in working order. By 0620 hours the liquid level had fallen below the 20% set value and the consequent alarm was accepted by the operator. The low level alarm did not have a trip function.

63 The nucleonic level sensing gauge had a range of 900 mm, and provided a means to verify the float gauge reading over the middle of its range. It had no direct control, alarm or trip function. The float gauge and the nucleonic mid points coincided and there gave equal readings of 50%. A 100% reading (nucleonic) was equivalent to 63% on the float gauge; while at 0% (nucleonic) the float gauge registered 38%.

64 There was an 'extra-low' level detection system on V305 comprising two float switches which were attached to the bridle assembly beneath the float gauge. Each consisted of a chamber with a pivoted float, movement of which was actuated when the liquid level inside it fell. This then broke a magnetic circuit, operated an electrical switch, and initiated audible and visual alarms. This system was also intended to close both flow control valves from V305 to V306 stopping the outflow of liquid and thus preventing gas breakthrough. Operation of this trip also prevented the valves from being opened until a safe liquid level was established in V305.

65 The liquid pressure from V305 was reduced solely by the throttle action of the flow control valves. However, in the original installation some pressure drop was effected by a power recovery turbine located in the line between V305 and V306, which the extra-low level trip system was intended to protect against gas breakthrough. The turbine was never used and was removed in the mid 1970s. A safety audit carried out in 1975 nevertheless confirmed a need to retain the extra-low level trip, because it was critical to prevent over-pressure in V306.

The audit also identified operational problems in controlling the level in V305 and recommended duplicate tappings on it for level detection instruments. This recommendation was not implemented. The nucleonic gauge operating over a restricted range was fitted instead. The audit recognised that the pressure relief valve on V306 could not cope with gas breakthrough.

66 In 1980 a study of the pressure reliefs to flare was carried out by a specialist contractor. It assumed that the extra low level trip system on V305 would function correctly and concluded that existing precautions precluded gas breakthrough. No recommendations were made for further pressure relief.

67 As part of the extra-low level trip system LIC 3-22 and HIC 3-22 valves each originally incorporated an electrically operated 'dump' solenoid to interrupt and release the air pressure on the valve diaphragm, thus causing the valve to close. The HIC 3-22 solenoid dumped when de-energised, but the LIC 3-22 solenoid dumped when energised. Thus if the electrical supply to the LIC3-22 solenoid failed, the valve would not close and therefore in this respect it failed to danger although the electrical supply was monitored by a 'trip-supply-fail alarm'.

68 The electrical supply wiring to the LIC 3-22 trip solenoid was found to have been deliberately disconnected at the control room and on HIC 3-22 the trip solenoid had been removed and bypassed. In consequence neither of these flow control valves could trip to close on extra-low levels in V305. It was thus possible to open the valves with little or no liquid in V305. Safety of this part of the plant had for many years thus depended solely on the vigilance of operators.

69 Disconnection of the LIC 3-22 trip solenoid was commented on in a 1985 memo by the refinery senior instrument engineer. A manuscript amendment probably made some years before on a wiring plan showed it was "*disconnected*

temporarily at the rear of the control panel". There are three possible reasons why the trip was disconnected.

- (a) It was considered part of the redundant turbine system and thought unnecessary.
- (b) Liquid in V305 vortexed and often caused the extra-low level trip to operate spuriously. At high throughput this caused production difficulties.
- (c) Because it was cumbersome to use the manual bypass valves (SP25) the operators wanted LIC 3-22 to open at levels below the extra-low trip so that, for example, V305 could be completely drained prior to shut down.

70 Many operators knew this trip was inoperative as they had taken the level of liquid in V305 below the notional trip point and the valve remained open. No assessment of the potential consequences was carried out before the trip was disconnected. Routine procedures for testing and defect reporting did not highlight its absence. This state of affairs was accepted by those concerned with the hydrocracker, at least up to the level of process supervisor.

71 The trip solenoid on HIC 3-22 was removed and bypassed in 1986 after being damaged in a fire. It too would not have closed on 'extra-low' liquid level and could be opened with a dangerously low level. There was therefore the potential for gas breakthrough as with LIC 3-22. The investigation revealed that HIC 3-22 remained shut and played no part in the incident, but the absence of its solenoid is considered by HSE to have been of equally serious potential.

72 Operators stated that the extra-low level alarm visual indication had been in continuous operation for many months until the light bulbs failed some time before the explosion. The alarm had been regarded as spurious. The extra-low level alarm circuit board was tested and found

to be in working order. The two float-switches were fire damaged but there was evidence to suggest that the first switch was incorrectly assembled, and that the small bore pipework to the second switch was blocked. The possibility thus existed that both extra-low level switches were inoperative.

73 Trend chart recorders provided a permanent record of aspects of the hydrocracker operation. However they were not synchronised and the information they provided needed to be interpreted with care and by reference to other evidence. Several of their pens were not working. The float gauge chart did register the falling liquid level in V305 in the 45 minutes prior to the explosion, as shown in Fig 12(A), but does not show the minutes before the incident when the liquid level fell, V305 emptied, and gas breakthrough occurred. Four minutes before the explosion the chart (Fig 12B2) shows a rapid fall in V305 pressure. This along with eye witness reports, which suggested that the pressure relief valve on V306 was lifting immediately before the explosion, confirmed that gas breakthrough had occurred. The rate of pressure drop could not be explained by other mechanisms such as emergency depressurisation.

74 There was no chart indication to confirm the pressure conditions in V306. The amine plant pressure registered no change which taken with other evidence confirmed that the gas output valve from V306 was shut and consequently this outlet for gas escape was closed. There was no alarm or trip on V306 for high pressure or over-pressure conditions.

75 The hydrocracker operated continuously. Shift hours were from 0600-1400 hours (day), 1400-2200 hours (back) and 2200-0600 hours (night). Each shift of eight operators is shown in Table 2. A ninth operator on shift that morning was a trainee. The senior boardman had primary responsibility for all control room operations, in particular the hydrocracker, with the junior

boardman controlling the hydrogen, vacuum and amine units. Operators were largely trained on-the-job by experienced colleagues.

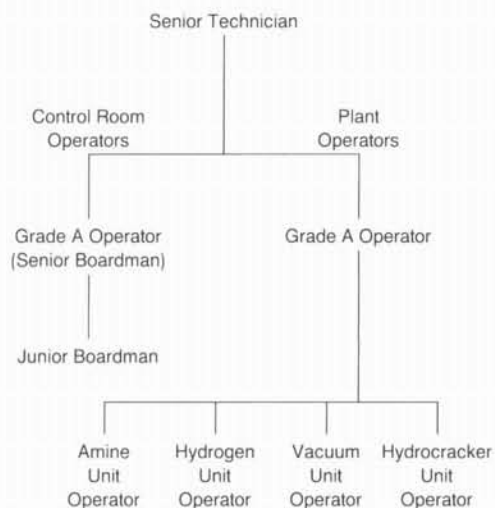


Table 2 Shift operator responsibilities

Causes

76 Operators denied taking action or making adjustments which could explain the incident. However all the evidence suggested that LIC 3-22 had been opened and closed on manual control at least three times after the shift changeover at 0600 hours. Liquid level in V305 fell and when LIC 3-22 was opened again just prior to the incident all remaining liquid drained away allowing high pressure gas to break through. LIC 3-22 did not close automatically because its trip solenoid was disconnected.

77 Despite the presence of steam trace heating, wax inside the float gauge and the small bore pipework to the extra-low level switches had been known to solidify when it was cold. The float gauge sometimes gave false readings and a number of operators mistrusted it. They placed more trust in the nucleonic gauge readings because the bridge itself was less prone to blockage. On that cold March morning the boardman paid no attention to the falling

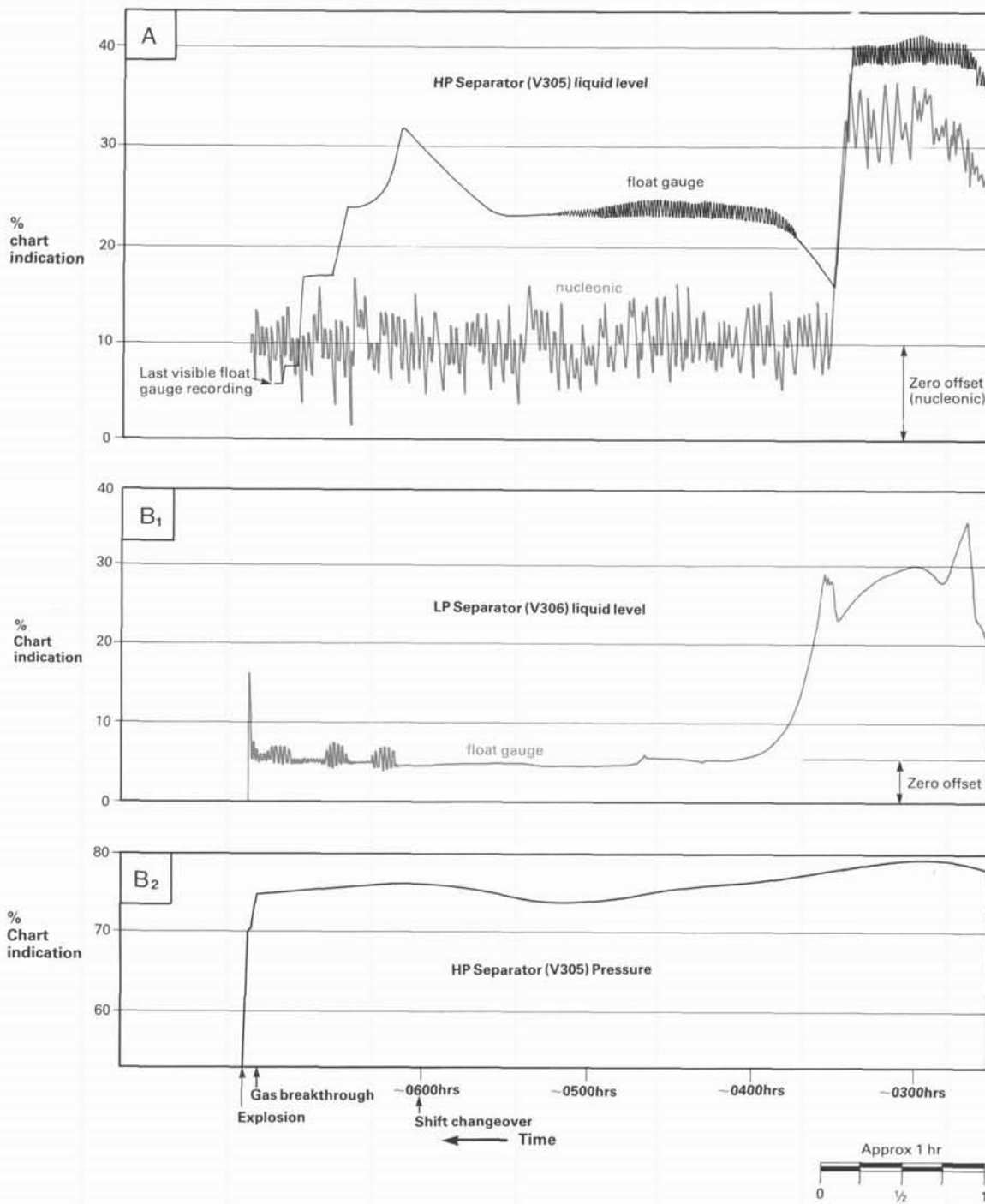


Fig 12 Diagrammatic representation of charts (traces enhanced and time corrected for clarity)

float gauge trace, assuming instead that the nucleonic chart reading which appeared steady at 10% reflected the actual level in V305. Unknown to him the pen had been offset so that a zero reading was shown on the chart as 10%. He was thus unaware of the actual level in V305 and of the imminent danger.

78 Liquid level in V306 was similarly measured by float and nucleonic gauges. The charts indicated that liquid flowed from V306 to the fractionator some hours prior to the incident and the gauges went off-scale. The evidence indicated that V306 then emptied requiring 17 000 litres to bring its float gauge on-scale. Fig 12B1 shows liquid surges in V306 corresponding to falls in the level of V305. The level also appears to rise in the minutes before the explosion. HSE calculated from this that V306 contained about 20 000 litres confirmed by calculating the amount of liquid transferred from V305 following closure of the outlet valve from V306 to the fractionator (para 80(b) refers).

79 That morning the hydrocracker was on standby following the TCO trip with feedstock from V308 (Fig 7) stopped. However, residual liquid from the reactors (V301 - V304) continued to pass into V305 by the action of the recycling gas, although diminishing over a period of hours. V305 level was controlled during routine steady operation by having a fixed flow through HIC 3-22 on manual and with flow variations controlled by LIC 3-22 on automatic. On standby, however, flow was erratic and LIC 3-22 on automatic would be too slow to cope with sudden increases. Because it responded more quickly on manual, this was the preferred method of operation, but in this mode the maintenance of safe levels required strict operator control. After about 0600 hours liquid flow had almost ceased and the boardman said he had HIC 3-22 and LIC 3-22 shut on manual. He was mainly concerned with the unexplained TCO, the vibration on C301 and conditions on the amine and downstream plants rather than the level in V305. However because prolonged standby operation was rare he

had no previous experience of it.

80 The following factors may account for LIC 3-22 being opened, and liquid level in V305 falling during standby operation:

- (a) In cold weather and on standby with no flow, wax could solidify in the unlagged and unheated HIC 3-22 and LIC 3-22 lines. To prevent blockages the valves were opened on manual to pass warm liquid through. Flow was verified by noting changes in V305 and V306 levels and in V306 pressure which rises as gas escapes from the liquid. Alternatively V305 was drained of liquid allowing gas to breakthrough and blow the lines clear of wax. Gas entering V306 was again verified by a pressure increase. With the reactors under standby conditions liquid transferred from V305 was not replaced. The duty boardman had not practised the above techniques nor had they been explained to him. However, he had been in the control room the previous day when a senior technician had blown gas through the lines in preparation for start-up. Another operator remembered that 2 years earlier there was an occasion when gas was heard surging into V306 and its pressure relief valve operated. Almost certainly this was gas breakthrough. However an incident was avoided by the boardman closing the flow control valve. This near miss was not reported to either supervisors or management and there was no investigation.
- (b) The fractionator feed valve (FIC 3-21) passed liquid significantly when closed using its control room controller, and V306 emptied. However before start up V306 required sufficient liquid in it to ensure that gas breakthrough to the fractionator would not occur. To ensure sufficient liquid it was therefore necessary for FIC 3-21 to be tightened (hand jacked shut) manually on plant and this was done. To get sufficient liquid level into

V306 for its float gauge to register, LIC 3-22 would then be opened on manual control.

- (c) Although unlikely, the array of similar controllers could have resulted in an operator turning the LIC 3-22 thumb wheel in error. He may then not have noticed the level drop in V305.
- (d) The operator believed the V305 nucleonic gauge chart recorder reading with its zero offset. In addition he was not aware of the extent to which the liquid level in V306 was below that which would show a reading on its float gauge. Thus if LIC 3-22 was opened in an attempt to establish a level of liquid in V306 and no instrument changes resulted, it could be concluded that LIC 3-22 had not opened. The valve may then have been opened further or for a longer period to get the levels to respond, whilst in reality levels were falling rapidly.

81 Opening LIC 3-22 on manual control to pass warm liquid or gas through the lines was permitted by supervisors. This necessitated bypassing the safety trips. Because the danger was recognised this was only supposed to be done under carefully controlled conditions and with extreme care. Operators were required to pay close attention to instruments! The shift instructions log book entry on 17 October 1986 stated:

"once all wax appears to have been removed, block in and leave for 2 hours, then check by opening LIC 3-22 carefully to avoid over-pressurising the LP separator. Repeat every 2 hours"

and again on 13 March, 1987 stated:

"with caution and care, sweep hydrogen from the HP through the LP and the multilocks to the fractionator to try to remove as much wax from the lines as possible".

This was clearly a dangerous practice the potential consequences of which were not fully understood.

82 Tests were carried out by HSE to establish the gas and liquid flow characteristics of the flow control valves. Water flow rates at comparatively low pressure were used to calculate the flow of hydrocarbon liquid which would have been expected in service at the 155 bar pressure drop between V305 and V306. The results for LIC 3-22, the valve which was opened are shown in Table 3. The variation between the HSE figures and the manufacturer's data at mid-range is attributable to the effects of in-service conditions and valve seat wear. Despite there being no means on plant for measuring flow between V305 and V306, operators estimated flow rates against percentage valve openings. Their estimates correlated closely with the calculated figures.

Table 3 Liquid flow characteristics of LIC 3-22 valve

LIC 3-22		
% Open	Manufacturers data	HSE values
	litres/min	litres/min
100	13 500	13 100
80	12 100	11 600
60	9 500	8 100
40	6 000	3 300
20	2 600	1 700
10	1 100	-1 100
5	500	-750

83 Gas flow characteristics of LIC 3-22 were obtained from the manufacturer and confirmed by calculation based upon the liquid flow test results (Table 3). A computer programme was then used to predict the expected pressures in V306, assuming hydrogen passing into it at 155 bar, as a function of percentage open of LIC 3-22. Flow through its pressure relief valve (PRV) and its estimated liquid content (para 78) were taken into account. The results are shown in Table 4 (columns 1 and 2). The time taken for V306 to reach its calculated burst pressure of 50 bar is shown in Table 4

(columns 1 and 3). The times shown commence once V305 is drained of liquid. It can be seen that if LIC 3-22 was opened less than 40% the maximum pressure in V306 would be less than 50 bar and it would therefore not rupture but would vent via its PRV. With LIC 3-22 open more than 40% the PRV was not of sufficient capacity to prevent rupture. These calculations therefore established that for V306 to explode LIC 3-22 must have been opened beyond 40%.

Table 4 Relationship between position of LIC 3-22 and pressure rise in V306 and time taken to reach burst pressure of 50 bar

<i>% Opening of LIC 3-22</i>	<i>Pressure bar (psig)</i>	<i>Time to 50 bar (based on the models used)</i>
9	14 (200)	Will not reach 50 bar
17	21 (300)	Will not reach 50 bar
23	28 (400)	Will not reach 50 bar
30	35 (500)	Will not reach 50 bar
36	41 (600)	Will not reach 50 bar
38	48 (700)	Will not reach 50 bar
40	53 (800)	108 seconds
60	-	35 seconds
80	-	25 seconds
100	-	22 seconds

84 The chart recording of V305 level (Fig 12A) ceased some time before the incident (para 73). The time taken after this for the incident to occur is the sum of the time to empty V305 of liquid and the time to raise V306 to its rupture pressure. The LIC 3-22 liquid flow characteristics (Table 3) were used to estimate its percentage open when levels in V305 were dropping prior to the explosion and to calculate the time for it to empty. The downward steps in the float gauge trace (Fig 12A) show that LIC 3-22 was open less than 5%. The final downward trend no more than 20 minutes before the explosion starts at 6% on the float gauge trace when 13 200 litres of liquid remained in V305 and in order to empty this amount in that time LIC 3-22 must have been opened much more. If it was for example 40% open V305 would empty in 4 mins and when added to the

time of 108 seconds to reach its burst pressure (Table 4) this would give a total time to the explosion of about 6 minutes. The precise timing of the opening of LIC 3-22 beyond the 40% position may never be known but the calculations demonstrate clearly the potential to over-pressurise V306.

85 An indication of events in the minutes before the explosion is provided by the chart (Fig 12B2) showing V305 pressure. It shows a drop in pressure of 18 bar (270 psig) over 4 minutes and then a rapid drop as V306 ruptured. Although the complexity of the high pressure system precluded using pressure drop information to determine LIC 3-22 position, close examination of the chart shows the rate of pressure drop increased within that 4 minute period confirming that LIC 3-22 opened further. The volume of gas represented by the pressure drop was calculated as being sufficient for V306 to reach its burst pressure.

86 When the control room was entered after the explosion, a supervisor reported that the LIC 3-22 controller was on manual and 100% open. Later, when seen by HSE Inspectors it was found fully shut and other controls were also in different positions from those first reported. The supervisor's report was correct, two operators who altered the controls confirmed it several months later. However no explanation for LIC 3-22 being fully open has been given. The reasons described in para 80 could account for it being opened on manual during standby. The hydrocracker controls were typical of the late 1960s and the following features could have led to operator error:

- (a) Errors could be made when assessing the volume or depth of liquid in V305 and V306 as their measuring devices related to different indicated lengths, not to each other nor to the content of the vessels.
- (b) False assumptions could be made about the time to discharge the liquid in V305 since there was no means of measuring flow other than

Photograph 7 LIC 3-22 and HIC 3-22 controllers



- by noting changes in liquid level. If that level was below the range of the level measuring devices the operator was working 'blind' further increasing the probability for error.
- (c) Errors could occur as controls of a similar appearance carried out different functions. If one controller was adjusted when the intention was to adjust another, a valve could move to a position not anticipated.
 - (d) In situations of high stress an error could be made if the manual thumbwheel controller (photo 7) were moved in the wrong direction. The valve could then be opened instead of closed. The LIC 3-22 thumbwheel action was to close the valve when moved from right to left but this was not clearly indicated. On some other controllers where the valve action was different, thumbwheels operated in the opposite manner. It is possible that an operator relying upon long experience could move a thumbwheel and not monitor the consequence of his action.
 - (e) Errors could arise if a valve controller was adjusted directly from automatic to manual mode without going through a balancing procedure and without checking the manual thumbwheel setting (Photo 7). The balancing procedure should ensure that the valve position on manual corresponds to the position on automatic before the change to manual mode is made. Failure to follow this procedure could lead to the valve moving to a position not anticipated. The LIC 3-22 controller operated in this manner.

Conclusions

87 The investigation established the following:

- (a) V306 was subjected to an internal pressure of about 50 bar, significantly

in excess of its normal working pressure and sufficient to cause it to explode.

- (b) V306 overpressurised when hydrogen at 155 bar entered it from V305.
- (c) The high pressure gas was able to pass from V305 because liquid in it had drained through an open valve.
- (d) The open LIC 3-22 valve formed the route for liquid and then gas to pass into V306. HIC 3-22 and one of the by-pass valves were closed.
- (e) LIC 3-22 was not on automatic control. Hence the possibility that the incident was caused by failure of the V305 float gauge, which provided level signals for automatic control, and its associated control circuitry, can be discounted.
- (f) LIC 3-22, its level indicator controller and its pneumatic positioner did not fail and the valve did not open of its own accord.
- (g) LIC 3-22 was selected on manual control, was more than 40% open and was very probably 100% open.
- (h) Safety shut off in the event of extra-low levels in V305 relied solely on the process flow control valves LIC 3-22 and HIC 3-22. There was no independent shut-off valve in the line from V305 to V306.
- (j) The LIC 3-22 dump solenoid wiring was disconnected about 5 years earlier and as a result it did not close on extra low level liquid level in V305.
- (k) The HIC 3-22 trip solenoid was bypassed in 1986.
- (l) The alarms on the extra-low level detection system had failed and operators were not alerted as a dangerous situation developed.
- (m) Because the hydrocracker was on standby the normal process routes from V306 were valved off so that gas entering could leave only via its pressure relief valve.

- (n) The pressure relief valve on V306 was not of sufficient capacity to relieve the maximum potential flow of high pressure gas to prevent overpressure.
- (o) Too much reliance was placed on operators for the safe control of flow from high pressure plant into a low pressure system.
- (p) The refinery was aware of the potential for gas breakthrough following audits in 1975 and 1980.

88 It was very dangerous not to have accurate knowledge of liquid levels at all times given that the safety trip mechanisms on the two control valves were inoperative. Excessive reliance was being placed on operators with insufficient appreciation of the risks associated with gas breakthrough. Without 'extra-low level' protection in V305, V306 was at risk of being overpressurised at any time when the maintenance of a liquid level in V305 could not be assured and/or was not under precise control. This was most likely when LIC 3-22 was on manual control, during start up, interruption to normal operation and standby.

89 The refinery had procedures for routine monitoring of interlocks, alarms, and trips, but on the checklist for the hydrocracker some were omitted. The detection, trip and alarm systems for extra-low liquid level in V305, had been inoperative for a long time and maintenance staff and operators presumed that these were no longer required. Training of new operators, carried out by experienced operators helped to perpetuate this misconception. Although the refinery chief instrument engineer noted in 1985 that the LIC 3-22 trip solenoid had been disconnected, this was not followed up.

Preventive measures to avoid the incident

90 The following preventive measures if taken, could have avoided the incident.

- (a) V306 should have had a high integrity automatic safety system to protect against gas breakthrough and also

pressure relief provision to cater for maximum anticipated gas flow rates. The safety shut off system should have included a secondary shut off valve in the line from V305, in addition to the control valves. Dual extra-low level detection should also have been fitted on V305 to provide independent shut off trips.

- (b) The trip systems and alarms as installed should nevertheless have been connected and in full operational order. They should have been included in comprehensive testing schedules. Defects should have been reported, recorded and actioned.
- (c) Changes to plant should only have been made after full consideration of the possible safety consequences.
- (d) Control room practices should have been monitored to detect possibilities for malpractice or error. Ergonomic factors in the design and layout of controls should have been periodically reassessed.
- (e) The problem of wax blockages in the level detection system on V305 and the associated small bore pipework should have been fully analysed. Steps should have been taken to reduce the likelihood of blockage by for example the use of larger bore pipework and monitored trace heating. The identification of blockages could have been assisted by dual level detectors and more sophisticated level instrumentation.
- (f) Wax blockages in the HIC and LIC 3-22 lines could have been prevented by the provision of lagging and trace heating.
- (g) Finally, a full analysis of the dangers and potential consequences inherent in the operation of the hydrocracker should have been carried out, and documented. Adequate safeguards should have been provided and all concerned should have been made aware of the potential dangers and necessary precautions.

Fire in a crude oil storage tank, Dalmeny: 11 June 1987

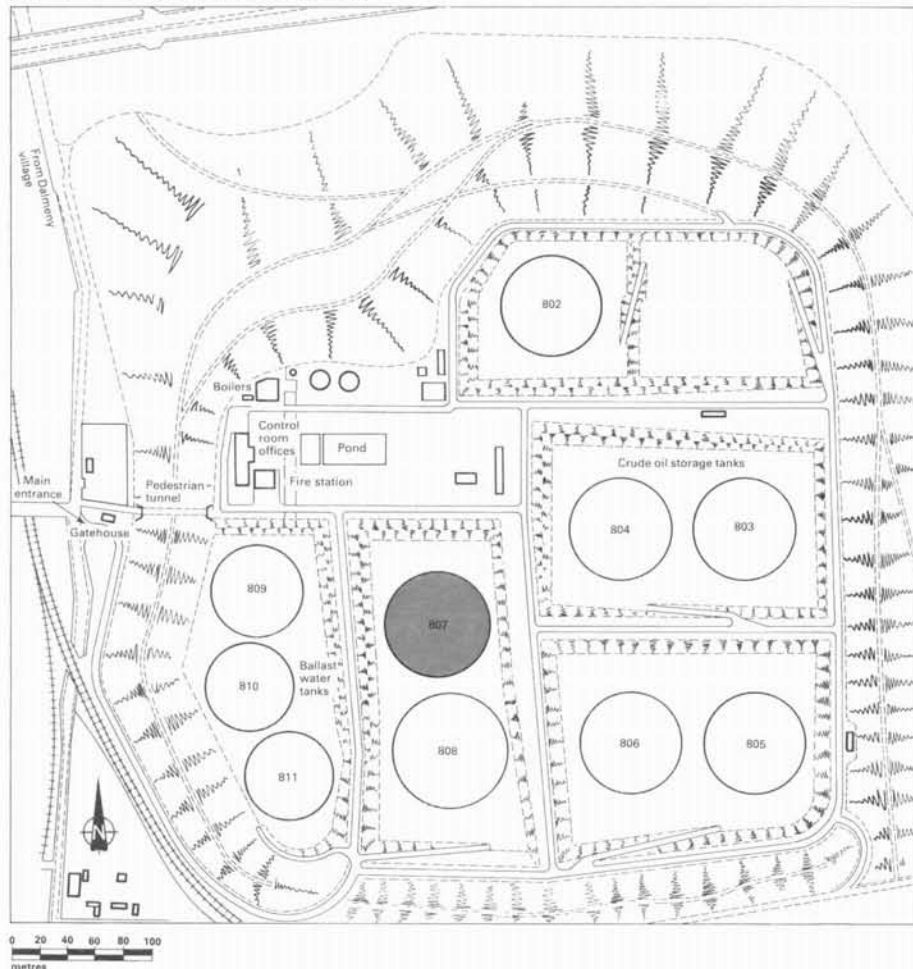
The site

91 The Dalmeny Oil Storage Terminal where about 30 persons are employed is approximately 20 km east of Grangemouth and is connected to the refinery's Kinneil gas separation plant by pipeline. Stabilised crude oil, destined for export by ship from the BP Hound Point marine terminal on the River Forth, is stored in seven floating roof tanks (T802 - T808). There are three fixed roof tanks used for storage of ballast water from ships. The site layout is shown in Fig 13. The floating roof tanks are identical, each being 78 m diameter, 18 m high with a capacity of 81 000 m³ (70 000 te). There are three pairs of tanks and a single tank located within 4 earthwork bunds. Tanks are called 'floating roof' as during normal service a roof will float on the surface of the oil so that it rises and falls with changes in the level.

Events leading to the incident

92 BP had identified that T807 required a routine inspection and overhaul. At a meeting on 10 November, 1986, they scheduled its removal from service for June, 1987 aiming for completion by the end of October. Thick sludge collects on the bottom of the tanks and a survey was carried out in April 1987 by external dipping through the support column ports on the roof, which established that approximately 1000 tonnes of sludge was present, situated in two banks, shown in Fig 14. T807 was withdrawn from service on 19 May and by 22 May had been emptied of crude leaving only residual sludge. The floating roof of T807 was resting on 219 support pillars, at a height of 2.1 m. It was then isolated by spading the inlet and outlet pipes. At regular intervals around the circumference of T807 near ground level there were four manways (600 mm diameter) and three ports (740 mm diameter) for motor operated agitators. The agitators, the

Fig 13 Dalmeny oil storage terminal



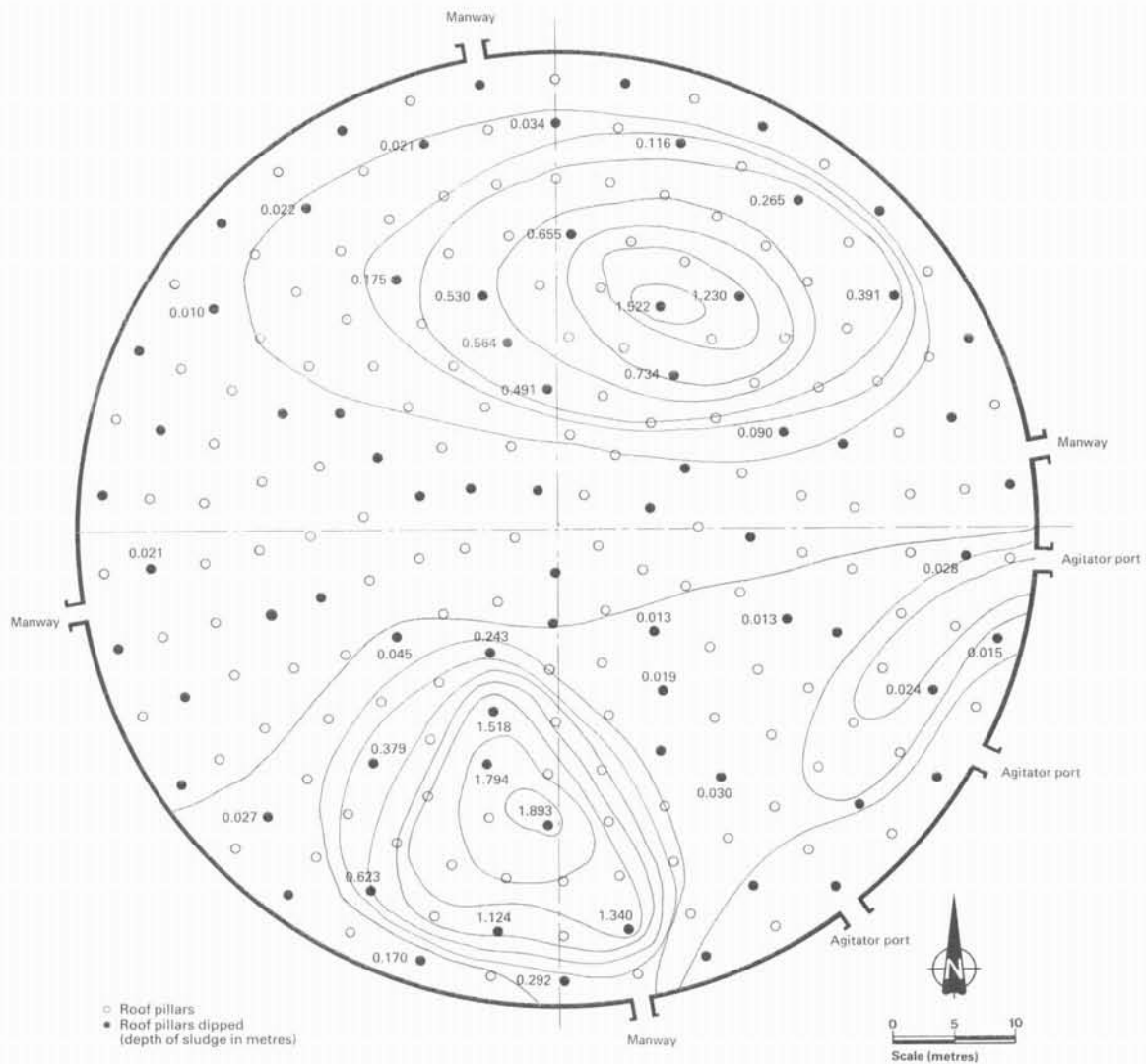


Fig 14 T807 sludge survey

manway covers and one of the three roof manway covers were removed. The tank was then allowed to ventilate naturally.

93 On 20 May the terminal engineer met representatives of several specialist cleaning companies to inform them of the nature and extent of the proposed work. On 28 May, a contract was awarded to the company which was already on site cleaning out ballast tank T809. After completing this work, the men and

equipment were transferred to T807 where work commenced on 2 June. For this there were eight contract employees including a working supervisor on site, all but three of whom had worked on T809.

94 The contractor was well known in the field of tank cleaning operations. They had successfully completed contracts on this and other sites. BP were satisfied of their competence when they awarded the contract. Procedures for tank cleaning

and sludge removal were decided by the contractor, although they were discussed with site management.

95 The tank and its bund area remained under site control and a permit to work was required to be issued before work could be started. T807 was not 'gas-free', ie not free from all flammable and other vapours. The evolution of flammable vapour with the risk of forming an explosive atmosphere was not considered sufficient to merit either mechanical ventilation or rigorous monitoring of the vapour concentrations inside the tank. However, as a precaution against potentially toxic effects, the contractor's employees working inside T807 were required to wear airline breathing apparatus supplied from a compressor located outside the bund. A hydraulically powered screw pump was located in the tank and the men used hand tools to pass sludge to its inlet hose. Sludge was then pumped through a 100 mm diameter flexible hose assembly, which passed through a tank manway, into the supply pipeline to T808 via a non-return valve. The diesel engine hydraulic power units were positioned immediately outside T807. The location of equipment was agreed with the terminal engineer.

96 On 4 June a hydraulically powered tracked vehicle fitted with a rubber edged wooden scraper was introduced to speed up the work. It was taken into T807 in pieces and assembled. The contractors continued working on the north bank of sludge. There were two teams of four which alternated every two hours. Three men worked inside and on duty outside was a fourth man and a BP safety services operator.

The incident

97 On 11 June the contractors started work inside T807 at 0630 hours, after their supervisor had checked on the re-issue of the permit to work with the terminal engineer. The team changeover which preceded the incident took place at 1230 hours. At 1320 hours the outside man looked in and shouted as he saw a ring

of fire surrounding the three men inside. As they ran to escape the flames one man fell but managed to struggle to his feet and escaped with a second man. The third who had been driving the vehicle ran in the opposite direction and did not escape. He died from the effects of asphyxiation and burns. The fire escalated rapidly with flames and smoke coming out of the open manways.

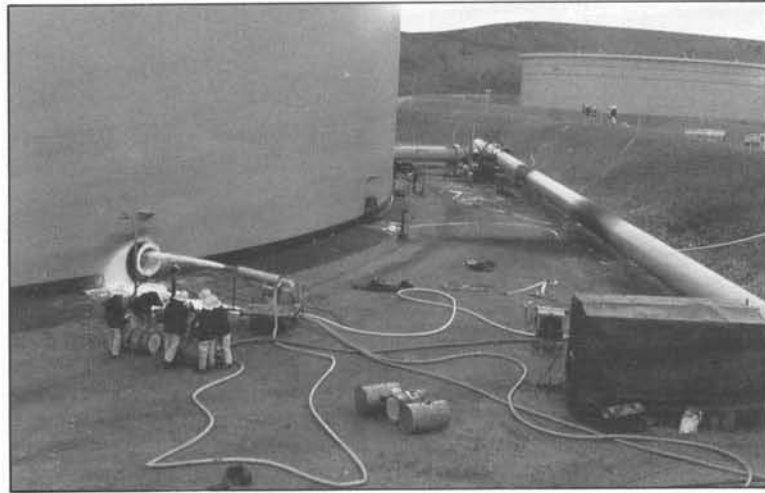
98 After a crew change the terminal fire tender was arriving at T807 to take up station after a brief absence. The terminal safety services operator and others took fire hoses from the tender and connected them to a nearby hydrant. Fire hoses had not been laid in position because on previous occasions they had been accidentally damaged. The fire was extinguished within about 10 minutes by the terminal fire crew. Lothian & Borders Fire Brigade arrived on the site at 1330 hours and for the remainder of the day were deployed in pumping foam through manways into the tank to keep the contents cool and to prevent re-ignition. The tank was allowed to cool and the body of the deceased, still wearing the remnants of breathing apparatus, was recovered on 12 June at 2100 hours.

99 HSE Inspectors were quickly on site and co-operated with the emergency services throughout the recovery phase of the incident.

Investigation by HSE

100 Crude oil is a complex mixture of hydrocarbons and a typical analysis of the crude in T807 is shown in Table 5. A sample of sludge from the outlet hose, identical to that in the tank prior to the fire, was tested to establish its flashpoint (the temperature at which it gives off vapour sufficient to cause a flammable concentration in air). It was found to be less than 0°C. The upper and lower flammable limits in air (the flammable range) of hydrocarbon vapour are typically 1.5% and 6%. The vapour is heavier than air.

Photograph 8 T807 at Dalmeny tank farm looking north



Photograph 9 Diesel engined unit near to T807 manway



Table 5 Typical analysis of stabilised crude oil

Constituent	% by weight
Stabilised gasoline	7
Benzine	14
Naphtha	18
Kerosene	12
Gas Oils	20
Heavy Oils and Tars	29

101 Many possible sources of ignition were considered including pyrophoric scale, static electricity, machinery malfunction, stray currents from the cathodic corrosion protection system, the location and maintenance of diesel engined equipment nearby, matches and smoking. Enquiries had commenced into these possibilities when a man admitted to smoking, stating that the fire started when he dropped his lit cigarette end.

102 A BP booklet entitled *A Guide to the Refinery Safety Regulations*, set out rules to be observed. Rule 5 stated that smoking was not permitted except in specified areas, and Rule 6 that matches and lighters were not allowed in the premises and must be deposited at the gatehouse. This booklet was not issued to all the contractor's personnel involved in T807. The temporary site entry passes for visitors and contractors had a condition that matches and other sources of ignition should be surrendered before entering the site. Such passes were not issued to the contractor's employees involved in cleaning T807.

103 Notices were posted at the main entrance to the terminal stating "no smoking within the installation" and "no smoking: all lighters and matches must be surrendered to security personnel at the gate". However, the entrance was unmanned and the gate was operated remotely from the control room using video camera surveillance and intercom. Terminal staff carried out no checks to ensure that contractor's employees complied with the rules. Unchallenged,

some men brought smoking materials on to site and into T807. It is not known when smoking inside tanks first started, but it appears that the practice was commonplace amongst certain contractor's employees who had smoked in T809 and had been smoking in T807 since work started. The contractor's foreman, in charge of the job was satisfied his men knew that smoking was allowed only in the designated safe areas. He never saw them smoking other than in these areas and had he done so he would have taken disciplinary action.

Undoubtedly, the men all knew that smoking outside designated areas was forbidden and that they would face disciplinary action if they were caught.

104 The men inside T807 were required to wear respiratory protective equipment (breathing apparatus or BA) to protect from the potentially toxic fumes. Vapour concentrations inside such tanks may typically approach 25% of the Lower Explosive Limit (LEL) and Table 6 illustrates the extent to which this exceeds the recommended exposure limits. Vapour concentration is not evenly distributed and depends on ventilation, ambient temperature, and the extent to which sludge is disturbed. Mechanical ventilation was not provided and thus the natural ventilation rate depended on wind speed and direction, and the passage of air through the open ports.

Table 6 Typical volatile constituents of crude oil

Volatile constituent	Lower explosive limit (LEL)	Concentration at 25% LEL (ppm)	Recommended exposure limit (ppm)
Pentane	1.4	3 500	600
Hexane	1.2	3 000	500
n-Hexane	1.2	3 000	100
Heptane	1.1	2 750	400

105 Some men did not appreciate the toxic hazards; neither did they realise the extent to which vapour concentrations would increase towards the floor of the tank. Some discovered that they could

see better in the dark, unlit conditions if they removed their BA face pieces or visors and they quickly became accustomed to the smell. As they felt no apparent ill-effects they concluded it was safe both to leave off their BA and to smoke. The deceased was a non-smoker and so far as is known, wore his BA at all times. Although experienced employees had received formal training some men were new to tank cleaning work and had received no such training. Basic training in the use of breathing apparatus was given by the contractor's supervisor. For some this involved only a short demonstration of how to fit the facepiece, operate the air regulator and deal with snagged air hoses or air supply failure.

106 The team involved mostly worked unsupervised and on the occasions when their supervisor, a member of the other squad, came in, they could return to wearing BA before he came close enough to see them. Although the supervisor was not aware of smoking and would not have condoned it, he had on occasions removed his breathing apparatus whilst inside the tank, in order to give verbal instructions to the men. From the outside of the tank it was impossible to see what was going on inside and the terminal safety services operator was unaware of these malpractices. The men ensured that they were wearing the correct equipment when entering and leaving to give the impression that it was worn at all times, and it thus appears that they deliberately deceived both their own supervisor and the terminal staff.

107 The survivors could not remember their exact position in the tank, other than they were working at the northern bank of sludge, and so the distance they were required to travel when the fire occurred is not known accurately. When the fire started flame is estimated to have moved across the surface at about 2 m/s and the fire may have spread to cut off the means of escape for the deceased. He alone was wearing his BA the hose of which may have impeded his escape by

becoming entangled on a support pillar. He may also have slipped or tripped over hoses or other equipment. Means of escape from the tank in case of an emergency, particularly in the event of fire, had not been considered and emergency escape exercises had not been practiced by the contractor. The outside man had no clear instructions about the action to take in the event of an emergency.

108 Although this incident resulted in a surface fire, there was the potential for an explosion had there been a sufficient volume of vapour at a concentration between the lower and upper flammable limits. Precautions to prevent this include ventilation and routine monitoring of vapour concentrations. Mechanical ventilation would not only have reduced the overall concentration of vapours in the tank but also minimised the extent to which local concentrations could have been in the flammable range. However the senior site engineer considered that such ventilation and vapour concentration monitoring were not necessary. He thought that concentrations would be above the upper flammable limit and that workmen wearing breathing apparatus were adequately protected. A terminal safety services operator undertook some monitoring on his own initiative although not fully aware of the instrument limitations. On the day before the accident he obtained a reading in T807 of 25% of the LEL. He did not know how to assess the significance of this reading which is in fact the limit at which consideration should have been given to stopping work. He took vapour level readings external to T807 daily and recorded these on the permit to work.

109 There were no detailed written procedures specifying the precautions to be taken during the cleaning of T807. The contract only made reference to general standards which were expected and stated *inter alia* that the contractor should ensure that his work methods "*are as safe as is reasonably practicable and that any danger to life and limb and the*

environment is minimised". The contract also stated that "all work will require the issue of permits by the employer (BP) but the employer reserves the right to suspend the permit at any time should he consider the area becomes unsafe."

110 Rigorous inspection of equipment used by the contractors was not carried out. Despite a BP requirement for internal combustion engines to be fitted with spark/flare arresters, a diesel engine hydraulic power generator located about two metres from an open T807 manway was found with a cracked exhaust manifold. There were no formal procedures for checking the equipment being taken into the tank.

111 In 1985 following similar tank cleaning operations, the terminal had received advice from HSE which recommended that consideration be given to the means of escape from inside tanks for persons wearing airline breathing apparatus because of the risk of air hose entanglement around roof support pillars.

Conclusions

112 The fire was started because an employee of the cleaning contractor deliberately disregarded a basic safety rule. He smoked in the tank which contained highly flammable vapours. He was not alone in this; two other men had also smoked in the tank. In his written judgement following the Fatal Accident Inquiry the Sheriff stated "They knew that it was dangerous. They wilfully shut their eyes to the fact that by doing so they risked causing a fire". While good site security and supervision may reduce the likelihood of smoking the Sheriff doubted whether such precautions would be adequate "against the perversity of workmen who choose to break all the rules" However, companies undertaking such potentially hazardous work must be rigorous in their staff selection procedures.

113 An important safeguard during tank cleaning operations involving flammable residues is the provision of adequate

ventilation. This should be sufficient to reduce the overall flammable vapour concentration, to avoid vapour pockets and to minimise the extent to which the vapour above the sludge surfaces may be in the flammable range. The effective control of ignition sources is of equal importance but in view of the ever present risk of fire, precautions for tank cleaning must also include provision for safe means of escape. Tank designers should give due consideration to the hazards of cleaning operations and the need for access and ventilation. Companies who carry out tank cleaning operations should produce a detailed method statement setting out clearly the safety precautions they intend to take.

114 "The preparation and operation of contracts in the Petroleum Industry: Health and Safety Guidelines" a publication produced by the Oil Industry Advisory Committee (Reference 3) refers to the care which should be taken in selecting and assessing contractors referring to, inter alia, management attitude, safety performance assessment, safety policy etc. Reference is made to the need to control contractors on site. Although the legal duties of employers described in section 2 of the Health and Safety at Work etc Act 1974 cannot be delegated, every employer is, as a general principle, responsible for those areas over which he can exert control. Site occupiers should recognise their special responsibilities relating to the overall control of their sites and should make provision for possible shortfalls on the part of any contractor (and his employees).

115 Site occupiers are advised to make it a condition of contract that they may:

- (a) *Inspect and approve where necessary any materials, substances and equipment provided by the contractor and specify any necessary conditions under which the materials or equipment may be used;*
- (b) *require the contractor to provide information on the health and safety aspects of the materials, substances*

and equipment to ensure that they conform to national specified standards;

- (c) *require evidence from the contractor that his personnel are trained and experienced enough to do the job competently and safely;*
- (d) *require the contractor to demonstrate that his employees are at all times adequately trained and instructed in the potential hazards associated with the owner-operator's operations or, as necessary, review the adequacy of the training, instruction and information given to contractor's employees to identify areas for improvements;*
- (e) *at any time - when a contractor is working within an area under the control of the owner-operator - inspect and audit the contractor's workplace and working methods and examine any record required by*

statute or, additionally, by the owner-operator's own accepted practices;

- (f) *require the contractor to stop work or prohibit a particular practice when he considers his activities may be prejudicial to health or safety.*

116 The circumstances of the accident demonstrate clearly the need to follow the advice set out in the HSE publication *Dangerous Maintenance - a study of maintenance accidents in the chemical industry and how to prevent them* (Ref 1) especially at paras 88 to 92. The report highlights key points on contractors.

- (a) *Is the competence of contractors properly evaluated?*
- (b) *Are contractors on site instructed in the possible risks?*
- (c) *Do contractors receive full information on the job to be done?*
- (d) *Are contractors properly supervised?*

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