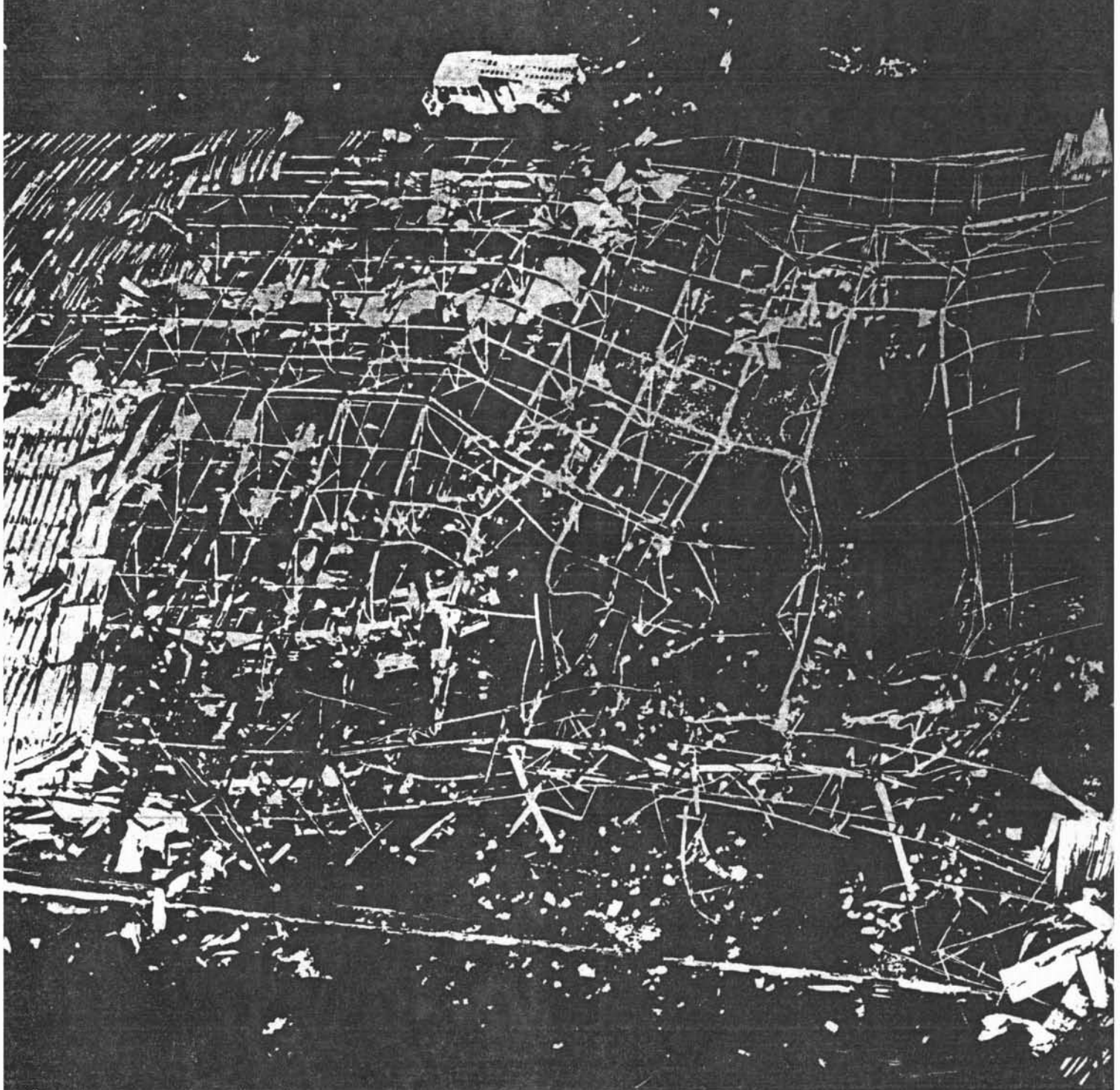


fire and explosion at
sheephead container depot, Renfrew
January 1977



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On 4 January 1977, a serious fire and explosion occurred at the Braehead Container Clearance Depot at Renfrew in Scotland.

The fire and explosion, which originated at a warehouse occupied by James Kelman Transport and Storage, completely wrecked that warehouse and the adjacent whisky bonded warehouse occupied by Clyde Container Services Ltd and also caused widespread window and roof damage to domestic, commercial, industrial and public property within a radius of a mile of the premises. The cost of the damage is estimated at some £6 000 000.

It was fortunate that, despite the extent of the damage, only twelve members of the public and one watchman were treated for shock and minor injuries.

After investigation had eliminated one cause of fire after another it was discovered that it had accidentally been started by three boys who had lit a fire to warm themselves at a den which they had made, during the New Year holiday, from cardboard cartons stacked beside the warehouse.

Subsequent experimental work tended to suggest that explosions of this nature and severity can be caused by the involvement of commercially pure sodium chlorate under the intense heat conditions of an industrial fire.

Introduction

1 About noon on 4 January 1977 a fire started in a warehouse at Braehead Container Clearance Depot, and spread rapidly throughout the warehouse. At 12.08 hours there was a rapid series of about five violent explosions, apparently involving the detonation of sodium chlorate stored in steel drums in the warehouse used by James Kelman Transport and Storage for holding miscellaneous goods. The blast caused damage, mainly extensive window damage, to about 200 properties within a mile of the depot, and twelve members of the public were treated for shock and minor injuries.

The depot

2 The depot consisted primarily of four large sheds built about 1942 for the storage of goods in transit by rail to and from nearby docks. Each shed was 30.5 m (100 ft) wide by 152.4 m (500 ft) long and 6.1 m (20 ft) high to the eaves. They were steel-framed buildings with walls and roofs of corrugated steel sheets coated inside and out with a bituminous laminate containing some chrysotile asbestos as a binding agent. The concrete floors were surfaced with a two-inch thickness of tarmacadam. The sheds and surrounding ground were owned by the Clyde Port Authority and had been leased to different occupiers over the previous eight years for storage purposes. This was mainly the storage of goods in transit including containerised goods going to and coming from ships and being distributed or collected by road transport.

3 The sheds were lettered A, B, C and D (see Appendix 4, Fig 2) and were occupied as follows:

Shed A James Kelman Transport and Storage

Shed B South Bank Transport Services

Shed C Clyde Container Services Limited with a majority shareholding by the Clyde Port Authority

Shed D The DCL Cooperage Co Limited who used this particular shed for the long term storage of wooden cask staves.

Use of Shed A

4 James Kelman Transport and Storage who employed about 30 people, obtained the lease on Shed A at the Braehead Depot on 14 August 1976.

5 At this depot the firm employed a general manager, a transport manager, an office girl, a mechanic and a fork lift truck driver. In addition, two to four lorry drivers operated from these premises.

6 The larger part of the storage space in Shed A was let on a weekly basis to the owners of the goods being stored. Kelmans had not previously stored sodium chlorate until they took over Shed A, although they had transported it for many years. The previous occupant of Shed A, Cordon Transport Services (Paisley) Limited, had stored there up to about 75 tons of sodium chlorate since 1974. The sodium chlorate, which was owned by Strathclyde Chemical Co Limited, had been supplied via Kemanord Limited, Marlow, Bucks, by Kemanord, Stockholm,

Sweden, where it had been manufactured. It was for subsequent sale for use as a weedkiller, and would be removed from these premises in small lots as required, mainly in the spring. Other goods stored at the time of the explosion included powdered milk, over one hundred combine harvesters, domestic washing machines, rubber tyres, glass bottles, and wooden pallets, etc. Some goods were expected to remain in storage for over a year but others were constantly moving in and out in the course of transit. There was an office at the western end of the shed, and at the eastern end there was an area equipped for running repairs to motor vehicles and included a small brick store. There were no internal separate walls other than those of the office and the small store. At the northern side of Shed A was a hard standing where containers were kept and minor repairs were carried out to containers which had been damaged in the course of transport use.

Storage and location of sodium chlorate and adjacent goods in Shed A

7 The sodium chlorate, 99% pure (Appendix 3) was contained in plastic bags inside steel drums, with steel lids secured by locking rings. The drums were of 25 kg (55 lb) and 50 kg (110 lb) capacity and were 30.5 cm (12 in) in diameter and about 30.5 cm (12 in) and 53.3 cm (21 in) high respectively. The total quantity in store at the time of explosion was 67 tonnes, in two 'stows' or rows extending across the shed from the southern wall. One short stow contained 16.6 tonnes (196 small drums and 234 large drums) and one long stow 50.4 tonnes (672 small drums and 672 large drums). Witness evidence as to the precise location of the sodium chlorate varied, but taking into account residual visual evidence it is considered that the locations shown in Appendix 1 are accurate to within about 0.9 m (3 ft).

8 The drums were stacked on wooden pallets measuring about 121.9 × 101.6 × 15.2 cm (48 × 40 × 6 in). Each pallet carried either a single row of twelve large drums, or twenty-four small drums arranged in a double layer. The palletised drums had been stacked by fork lift trucks, standing about four pallets high in the small stow i.e. about 2.7 m (9 ft) high, and up to six pallets high, i.e. some 3.6 to 4.2 m (12 to 14 ft) high in the large stow. There was consistent evidence that the storage of sodium chlorate was tidy and that there had been no damaged drums or spillage.

9 The smaller stow of sodium chlorate was ranged round by milk powder with a space of between 0.3 and 0.6 m (1 and 2 ft) between the sodium chlorate and milk powder. The extent of the milk powder storage is uncertain but it is estimated that there was about 150 tonnes, stored in paper sacks mostly weighing 25 kg (55 lb) each, stacked 30 or 40 on a pallet and mainly two pallets high i.e. about 1.8 to 2.4 m (6 to 8 ft) high. There was frequently spillage of powdered milk from damaged paper sacks, but this was regularly cleaned up. The large stow of sodium chlorate had, on one side, stows of milk

powder, and on the other, stows of empty glass bottles contained in cardboard boxes and palletised. On either side of this stow of sodium chlorate there were spaces of some 0.3 to 0.6 m (1 to 2 ft). The height of the palletised glass bottles was, as far as can be ascertained, about the same as the sodium chlorate, i.e. 3.6 to 4.2 m (12 to 14 ft).

The fire and explosion

10 Close to mid-day on the 4 January 1977 fire was observed emanating from Shed A, by several workers at Braehead Electrical Power Station and a telephone call to summon the fire brigade was put through from the Power Station which stands about 160 m (175 yds) from Shed A across open ground. Several men who observed the fire, saw reddish yellow flames and black smoke coming from the base of the side wall at the rear of Shed A. This was in the vicinity of the loading platform by the sliding door indicated in Appendix 4, Fig 5. Within about five minutes the fire spread along the base of the side wall and then up the walls to the roof. The smoke increased in density and volume and began discharging from all the roof vents. Witnesses' descriptions of the fire and explosions varied slightly but it is clear that there were two small explosions like gunshots, followed within a second or so by a severe explosion, some witnesses say two, followed by a rapid sequence of three or four lesser explosions. One witness described the visual effect of the main explosions as being a ball of orange red flames shooting through the roof and another ball of flames shooting through the northern wall towards the power station. Another witness at the gatehouse of the power station described how he was blown over by one blast, then regained his feet and entered the hallway to the gatehouse where he was blown over by a second blast.

11 From witnesses' accounts, the initial fire was followed by a rapid spread of flames throughout the building, which happened within a few minutes due to the burning of the bitumen coating on the corrugated steel sheet cladding of the building. The fire raged for some five to ten minutes before the explosions. Strathclyde Fire Brigade logged the first report of the fire at 12.05 hours and the explosion at 12.09 hours. The local Renfrew Fire Brigade were attending another incident when the first call was received.

12 As 4 January was a public holiday in Scotland, there was only a security watchman present on the premises at the time. He had just seen the fire and was returning to his office to telephone the Fire Brigade when he was blown off his feet by the explosion. After treatment for shock and minor cuts he returned to the site to help with enquiries. The major explosions resulted in severe blast damage to numerous properties and the spread of debris over a wide area, as well as transmitting fire to Shed C (see para 25 and Appendix 4).

Investigation of the occurrence

13 In the afternoon of 4 January 1977, HM Principal Inspector of Factories of the General Manufacturing

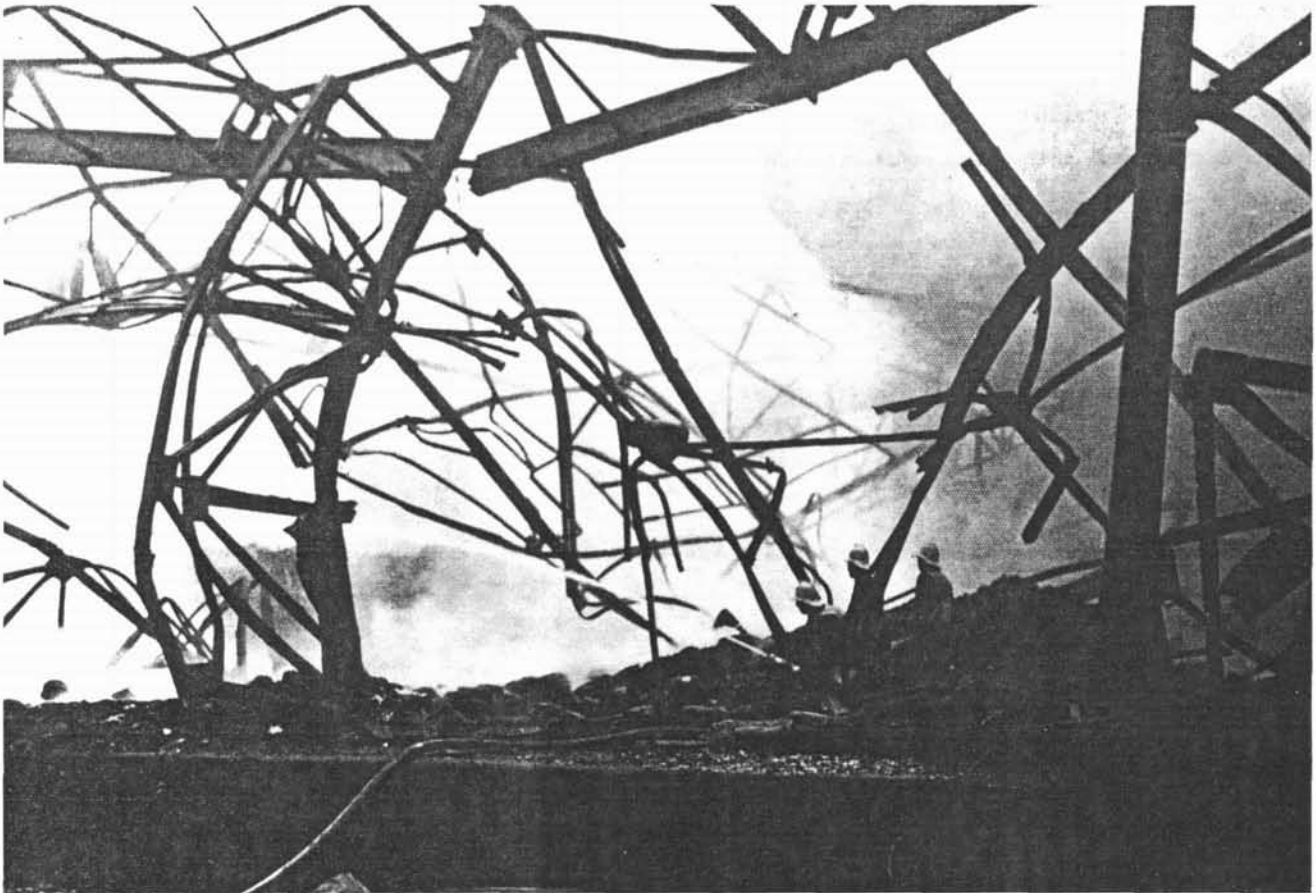


Fig 1 Fire-fighting at the seat of the blaze in Shed A (Courtesy of the Firemaster, Strathclyde Fire Brigade).

Industry Group covering South West Scotland, accompanied by other inspectors of the Health and Safety Executive (HSE) who had also heard the explosion, made their way to the site and began making preliminary enquiries. The Area Director for the West of Scotland visited the scene of the explosion and made arrangements for technical and scientific supporting staff to be provided to assist in a full investigation.

Strathclyde Police had established a control centre and sealed off the area, and Strathclyde Fire Brigade were heavily committed to fire fighting operations in Sheds A and C. The Principal Inspector of Factories collected initial examples of sodium chlorate and milk powder ejected by the explosion. The detailed investigation by the HSE began on the following day, 5 January 1977, with the Principal Inspector of Factories in charge of the site investigation under the direction of the Area Director and with the assistance of specialist inspectors of the HSE. On the first day of the investigation, HM Inspector of Explosives from London and the Superintending Specialist together with Chemical Inspectors from his Field Consultant Group in Edinburgh attended the site. At the same time Strathclyde Police were involved in a major investigation of the occurrence and Strathclyde Fire Brigade were also making enquiries into the origin of the fire. The police maintained a control and communications centre on site which facilitated the co-ordination of investigations. Early in the investigation it became evident from the damage and location of

craters that the sodium chlorate was the essential element in the explosion but difficulty was experienced in determining the origin of the fire and the precise way in which the explosions occurred.

14 On 6 January the mobile laboratory of the HSE Field Consultant Group was brought onto the site and scientific officers began to plot the location of outlying sodium chlorate drums which had been projected as missiles (see Appendix 4, Fig 2). They were also able to check on the residual burnt covering of the corrugated steel sheds, flakes of which had been handed in by members of the public from as far away as Bearsden, over 6.4 km (4 miles) from the site of the explosion. On analysis this was found to contain chrysotile asbestos.

15 A meeting was held on site between representatives of the HSE, Police, Fire Brigade, James Kelman Transport and Storage and the Clyde Port Authority to discuss the collection and disposal of the sodium chlorate, which because of its contamination was considered to be particularly hazardous as a further fire and explosion risk and perhaps poisoning risk. The police maintained a day and night patrol of the site and outlying areas until the contaminated sodium chlorate had been collected and disposed of.

16 As it was difficult to determine the source of the initial fire, HM Electrical Inspectors of Factories joined the investigation.

17 On 7 January 1977, aerial photographs of the site were taken and collection of the outlying sodium chlorate drums began under the supervision of the HSE Field Consultant Group. An incident investigation team arrived from the Research and Laboratory Services Division of the HSE in Buxton, and over the next two days photographed the site, carried out outlying damage surveys (see Appendix 4) and made measurements for the preparation of a site plan of the explosion (see Appendix 4, Fig 5). A meeting was arranged at the Police HQ in Paisley between the Police, HSE and Fire Brigade together with their various advisers to review progress in the investigations. The oxidising properties of sodium chlorate were discussed and concern expressed about what was considered to be the hitherto unrecognised explosive potential of pure sodium chlorate alone, which appeared to have been demonstrated in this incident. Several possibilities as to the ignition of the initial fire were discussed but no clear cause was evident at that stage in the investigation.

18 Investigations by the HSE team continued on 8, 9 and 10 January with HM Inspectors of Factories (Fire) also assisting because of the difficulty in determining the source of the ignition. Further samples of the milk powder and sodium chlorate were taken from points close to the centre of the explosions, and the Principal Inspector took possession of the remains of an electric fire and of an acetylene bottle, by the authority granted him under Section 20 of the Health and Safety at Work etc Act 1974. By this time all the outlying sodium chlorate had been removed and the police then left the site. The Principal Inspector of Factories posted notices directing that the remains of the eastern half of Shed A and contents should be left undisturbed until inspectors had completed their examination and investigation, as authorised under Section 20 of the HSW Act. The removal within the site of sodium chlorate and asbestos waste was excluded from this directive in view of the need to deal quickly with the hazards presented by these materials.

19 On 12 January at the request of the Area Director, HM Senior Construction Engineering Inspector from the Scotland Field Consultant Group of the HSE visited the site to advise about present stability and subsequent demolition of the remains of Sheds A and C. He was of the opinion that parts of the remains of the sheds were in danger of progressive collapse and an immediate voluntary evacuation of the remains of the buildings was agreed and arrangements were made for a meeting with Clyde Port Authority, the owners of the premises, at their Head Office the following day. At this meeting the dangers of collapse of the structures, the risk of explosion of sodium chlorate remaining inside the buildings, and of the disturbance of asbestos waste were discussed. Renfrew District Council were also represented at this meeting. Arrangements were agreed for the entire site to be left undisturbed until the owners had engaged a Consultant Engineer and Demolition Contractor.

20 On 14 January a meeting was held between the Police, Fire Brigade, and HSE at the Police HQ in Paisley

to discuss what progress had been made with the investigation. The HSE were coming to the conclusion that an electrical source of ignition or accidental source of ignition was unlikely and that the fire had been started in the vicinity of the sliding door at the rear and north side of Shed A. Pursuing enquiries, the police interviewed three boys aged 9 to 11 years old on 15 January and learned that the boys had set fire to cardboard cartons outside the sliding door at the rear of Shed A.

21 On 27 December, prior to the New Year holiday, this door was found to have been damaged. A corrugated steel sheet had been partly torn away leaving a hole in the door; this hole was temporarily secured from the inside and covered on the outside by placing pallets carrying folded cardboard cartons in position against the door. During the New Year holiday period the boys had used some of the cardboard cartons to make a 'den' against the shed. About mid-day on 4 January, as the weather was cold, the boys lit a fire, which in turn set light to the 'den'. They were unable to control the fire and ran away. The burning cardboard quickly set fire to the bitumen coating on the outside of the corrugated sheeting of the wall of Shed A and the fire spread rapidly.

22 After the discovery of the origin of the fire, many health and safety problems in dealing with the aftermath of the event still remained. On 18 January, representatives of the HSE, including HM Inspector of Explosives from London, convened a meeting at the Scotland West Area Office of the HSE with representatives of the Clyde Port Authority and their Engineering Consultant and Demolition Contractors. The hazards presented by and precautions needed during the demolition operations were discussed and the consultants engaged by the Clyde Port Authority subsequently exercised control over the clearing and demolition operations in liaison with the HSE. The directions of the Principal Inspector of Factories to leave the area affected by the explosion undisturbed were progressively relaxed and finally removed on 15 February 1977 when the investigation on site was considered to be essentially complete. The residual risks are discussed further in paras 51 and 52. Analyses of sodium chlorate samples were carried out by the Occupational Hygiene Laboratories of the HSE (see Appendix 3), and experiments in relation to the explosive properties of sodium chlorate were dealt with by HM Explosives Inspectorate (see paras 41 to 48).

Damage caused by explosion

23 The total cost of the site damage was estimated at about £6 000 000, which does not include broken windows in some 200 houses and shops in Clydebank and Renfrew.

24 The extensive damage caused to Shed A in the explosion is clearly shown in Fig 2 where an impression of the scale can be gained from noting the two men standing in the bottom left-hand corner. Flying debris, consisting mainly of open drums containing residual sodium chlorate, corrugated steel roofing sheets and

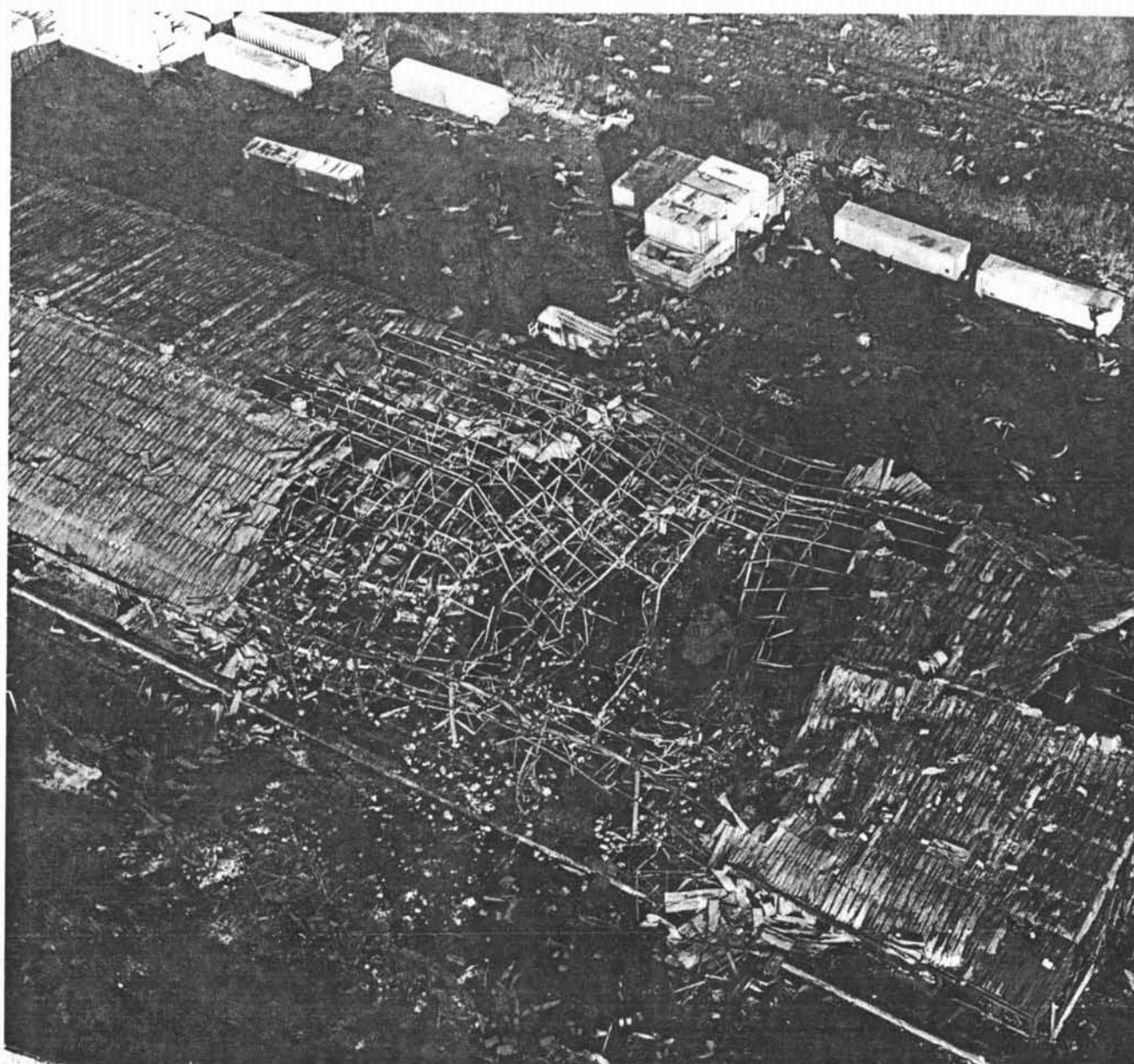


Fig 2 The seat of the explosion in Shed A.

burning pieces of timber from the pallets, was distributed mainly over the area shown in Fig 3 with a distribution pattern as indicated by that of the sodium chlorate drums shown in Appendix 4, Fig 2. Pieces of steel roofing sheets were reported as having fallen up to 2.8 km (1.75 miles) from the site of the explosion. Pieces of the lighter debris from the burnt bituminous covering of the roof sheets were scattered over an area extending more than 8 km (5 miles) from the explosion in the direction of the south-westerly wind, estimated at 14 knots according to recordings at nearby Glasgow Airport.

25 The blast from Shed A blew in the side wall and doors of Shed C and the evidence indicates that the blast travelled right through Shed C, blowing out the opposite side of the shed, which can be seen in the foreground of Fig 3. Burning debris was seen falling over the fuel tanks of the nearby power station. These tanks, which are prominent in Fig 3, have a maximum capacity of 30 000 tonnes of heavy residual fuel oil. This fuel storage

was not affected by the explosion but the evidence of burning debris in this area lends force to the view that burning debris was projected into Shed C. The main damage to Shed C however arose from the subsequent fire involving large quantities of whisky and other spirits. The fierceness of the fire involving whisky is indicated in Fig 4 taken at the east end where the whole roof collapsed as the supporting steel stanchions bent in the intense heat. There had been over 20 000 cases of whisky and eighty barrels of spirits, together with general cargo, in Shed C, which constituted a bonded warehouse. Shed C was the only part of the depot which had a security fence and was under the surveillance of a guard at the time of the explosion.

26 Both Sheds B and D suffered blast damage, particularly the end wall of Shed B next to the site of the explosion. Neither of these two sheds was affected by fire although several drums of sodium chlorate landed on the roof of Shed B and one drum was found inside the shed.

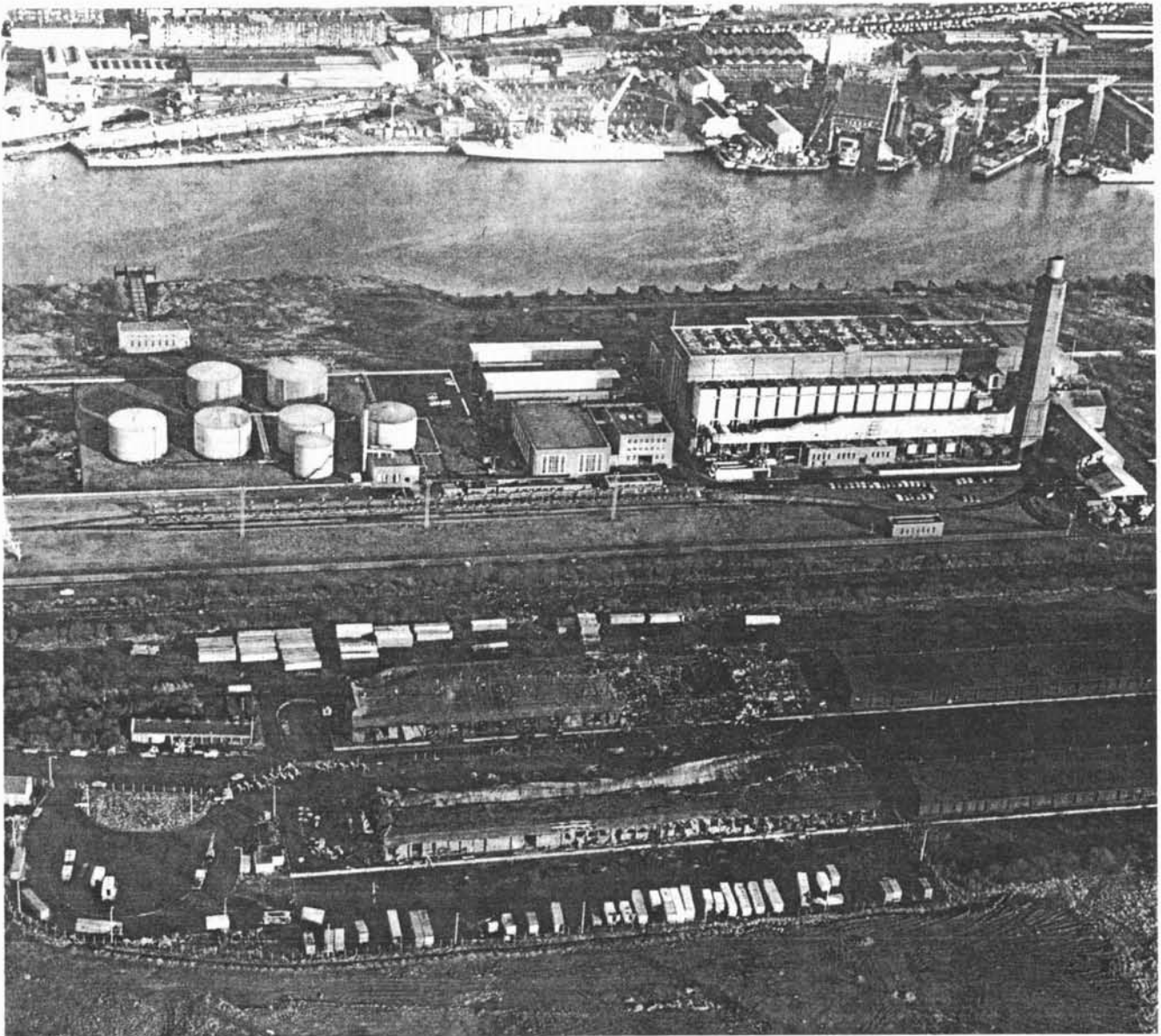


Fig 3 General aerial view of the damaged site.

Numerous unbroken green glass bottles were found lying in the corrugations of the roof of Shed B; these had obviously been ejected from the site of the explosion.

27 A damage survey report by the Research and Laboratory Services Division (RLSD) of the HSE is given in Appendix 4.

Conclusions on the initial fire

28 Over a period of ten days extensive enquiries were made by members of HSE and Strathclyde Police to try to determine the source of the initial fire. Numerous possibilities were considered and in particular a detailed investigation of the electrical installation of Shed A was undertaken by HM Electrical Inspectors of Factories who were able to eliminate a substantial number of electrical possibilities as likely causes of the fire.

29 It is clear that the spread of fire on the bitumen coating of the sheets was very rapid, particularly on the northern wall of the shed and in the eastern half of the

inside of the shed. This fire-spread took between five and ten minutes, or at the most fifteen minutes, according to varying eye witness accounts. There is little doubt that the interior roof of the building would have been well alight and that flaming droplets of bitumen would have been falling to the floor. With a moderate wind blowing from the south west there would be ample air entering underneath the entire length of the south side of the shed from the fail spaces of the sliding doors. It is likely that immediately before the explosions the fire would be intense on the south wall of the building in the vicinity of the stacks of powdered milk in paper bags and the small stow of palletted sodium chlorate.

30 The two minor bangs described as 'like gunfire', which occurred immediately before the main explosions, are largely a matter for conjecture, but could have been due to explosions of the fuel tanks of some of the combine harvesters which contained up to one pint of diesel oil. This is a likely explanation as it was noticed that some of these tanks on the combine harvesters had exploded in the

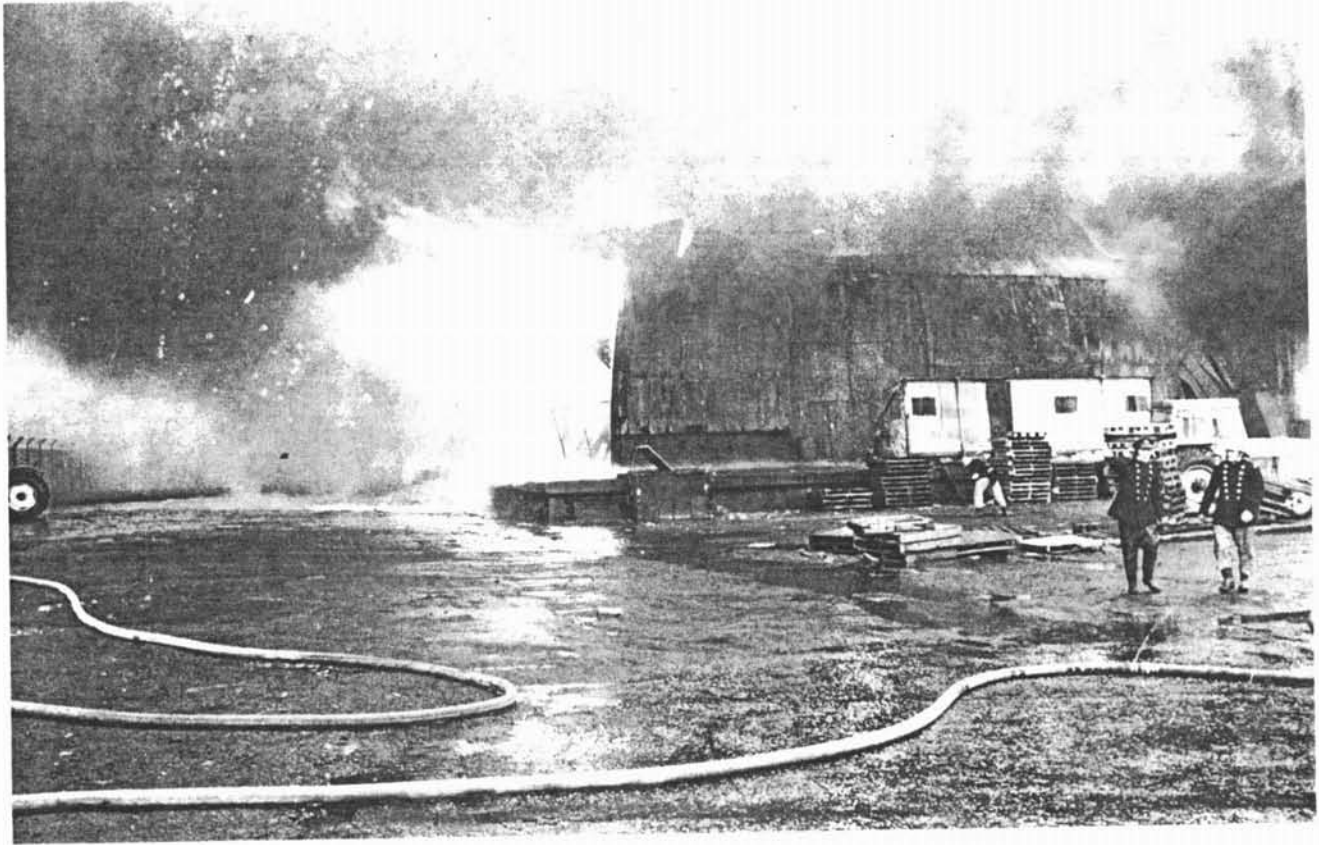


Fig 4 Whisky ablaze in Shed C (Courtesy of the Chief Constable Strathclyde Police).



Fig 5 Crater 3 and the main damage area of combine harvesters.

middle of the shed near the sources of the fire (Fig 5). Some drums in the north west corner of the shed, which had evidently contained oil, were seen to have exploded and it is also possible that these could have been responsible for the first two bangs.

Conclusions on the explosion

31 The damage at the seat of the explosions was consistent with explosions having taken place at the craters numbered 1 to 5 in Appendix 4, Fig 5. Craters 1 and 4 (Fig 6) were clearly caused by the principal explosions and their location coincided with that of the sodium chlorate prior to the explosion (as shown re-constructed in Appendix 1) where the sodium chlorate would have been intensely heated by the fire. Fig 7 shows the uprooted stanchion in crater 4. This stanchion and its foundation had been completely uprooted with its foundation from a depth of some 0.6 m (2 ft) and was displaced inwards 0.9 m (3 ft), which was consistent with the whole roof area having ballooned upwards at the time of the explosion. The disintegration of the steel framework of the roof had been finally brought about by the failure of bolts, but at least one of the roof truss bracing members was found to have completely sheared at the time of the explosion.

32 Remains of 1520 sodium chlorate drums were identified from the initial stock of 1774 drums, leaving 254 drums unaccounted for. From the reconstruction, from witness evidence, of the position and conditions of storage of the sodium chlorate, together with the evidence of blast damage and the position of the craters in the floor

of Shed A, it is concluded that part of the stock of drums of sodium chlorate exploded in the fire and that the explosions were caused without the sodium chlorate mixing with a contaminant, that is to say, drummed sodium chlorate exploded. The problems raised by the behaviour of sodium chlorate in this way are discussed below.

33 Estimates of TNT-equivalent based on observation in the far field (broken-window damage) may vary due to variations in the available experimental data on which the estimate is based and in the climatic conditions at the time of the incident, and to the inexact knowledge of the blast pressure profile generated by a series of explosions.

34 Estimates based on crater size and observations close to the centre of the explosion are subject to uncertainty due to lack of precise knowledge of the explosion characteristics of the material, the effect of surrounding structures and obstructions to the free passage of a blast wave.

35 Recognising the variations possible in the figures of TNT-equivalent, depending on the method used for assessment, it is possible that the estimate of 225 kg (500 lb) by HM Inspector of Explosives (see Appendix 2, para 7) is too low, whereas the estimate of 820 kg (1800 lb) by RLSO (see Appendix 4, para 14) following a far field damage survey is too high. A value between these limits is probably close to the truth. However the actual figure for TNT-equivalent does not affect the contribution made to the investigation by either party; the use of both methods permits a closer estimate to be made in the difficult circumstances of this incident.



Fig 6 The major crater, No 1 (App 4, Fig 5), with piled remains of milk powder behind.



Fig 7 The uprooted stanchion with crater No 5 (App 4, Fig 5) in foreground.

Discussion

36 Sodium chlorate is classified as an oxidising agent and not as an explosive. The only explosive potential envisaged in the relevant literature is that when it is mixed with a combustible contaminant; its explosive and unpredictable behaviour is well known. The National Fire Protection Association of America classifies sodium chlorate as a Class I oxidiser which does not infer that it is particularly dangerous as an oxidiser (see NFPA Code No 43A 1974). Explosive reactions of the materials alone are not envisaged until Class 4 oxidisers are reached.

37 Recommendations concerning sodium chlorate vary. The code referred to above states that: "storage in non-combustible containers in combustible buildings is not limited as to quantity or arrangement except that the distance to combustible walls shall be at least 2 ft". The Fire Prevention Information and Publications Centre recommends storage in a detached or non-combustible building or in a room separated from other parts by fire resisting walls and floors (see Information Sheet H7 October 1972).

38 Transport of sodium chlorate by sea and air is not subject to undue restriction and is dealt with by codes of the Inter-Governmental Maritime Consultative Organisation and the International Air Transport Association. (See IMCO Class 5-1 and IATA Packing Code 500). The transport emergency card issued by the European Council of Chemical Manufacturers Federations states, for sodium chlorate: "Nature of hazard – oxidising agent; may re-act with combustible substances creating fire or explosion hazards; heating will

cause pressure rise with risk of bursting; contaminated material, e.g. clothing, ignites more readily".

39 In seeking to explain the mechanism by which the explosion in Shed A occurred, the generally held view at that time, that commercially pure sodium chlorate would not be expected to detonate even under intense heat and conditions of confinement such as existed in this case, did not accord with the evidence of the explosion. The HSE therefore decided to undertake a research programme to investigate the behaviour of drummed sodium chlorate under fire conditions and re-assess the explosibility of this material.

40 This decision was reinforced when enquiries revealed that a previous similar explosion had occurred in Hamilton, Lanarkshire, in March 1969, when 20 tonnes of sodium chlorate in timber casks and metal drums exploded in a fire which wrecked the haulage contractor's warehouse, where the material was stored. Similar events involving either potassium or sodium chlorate were found to have occurred in St Helens in Lancashire in 1899, in Manchester in 1908, in Liverpool in 1910, in a Thames barge in Poplar in 1947 and in a cargo ship in Barcelona in 1974.

Subsequent experimental work

41 The object of the experimental work was to test the hypothesis that the behaviour of sodium chlorate is not dependent on the expeditious mixing of possible organic fuels with the chlorate oxidiser, as was often suspected, but is more associated with the basic performance of the

material under severe conditions of thermal decomposition.

42 The Research and Laboratory Services Division of the HSE mounted a series of fire trials at Buxton in which test drums of sodium chlorate purchased from the owners of the material in the Braehead Warehouse, were placed inside fires and their performance monitored.

43 The fire trials began with a single drum of sodium chlorate being placed in a bonfire of standardised content, size and construction. The lid was blown off the drum but there were no further results.

44 Increasing the fire intensity, by the addition of loose sodium chlorate to the bonfire prior to ignition, failed to cause an explosion of the sodium chlorate in the drums.

45 In the final Buxton experiment, a double size bonfire was built surrounding three 50 kg (110 lb) drums of sodium chlorate, and a drum of sand was placed above the centre drum to aid confinement. The drums on either side of the centre one were punctured with the holes facing the centre drum to facilitate flame impingement. Again loose sodium chlorate was spread in the fire prior to ignition. The result was a very intensive burning of the fire with brilliant white radiation and audible jetting noises from the impinging flames. However, apart from a few cracks and bangs there was no explosion of sodium chlorate, although the centre drum was totally consumed by the fire.

46 After considering the evidence of the Buxton fire trials (which had been carried out in the open), together with the previous incidents, it was decided to simulate a stack of sodium chlorate under the mild confinement such as would exist in a warehouse. The previously known explosions involving chlorates had occurred in warehouses, storerooms and ships' holds where heat generated would not easily escape in the same way as from a fire in the open and the latter would possibly fail to achieve the critical heat condition of a true industrial fire.

47 With the co-operation of the Ministry of Defence and the Home Office a further experimental fire test was conducted at a test range in East Anglia. A stack of thirty-six 25 kg (55 lb) drums of sodium chlorate formed the centre piece of a large bonfire built inside a three-sided, roofed enclosure. Once again loose sodium chlorate was added prior to ignition, to increase the intensity of the fire. Six-and-a-half minutes after ignition and 1½ minutes after the more intense fire associated with the involvement of the loose chlorate, an explosion occurred, followed, seconds later, by a second explosion. Pieces of drum were hurled out of the fire and blast gauges placed at a distance of 6 m (20 ft) were uptooted.

48 The evidence from this trial supports the hypothesis of the potentially explosive behaviour of pure sodium chlorate under intense fire conditions. The implication of this finding is further discussed in para 62.

Risks to the public

49 In view of the extensive damage, particularly window damage, to houses and commercial and individual buildings with a radius of about one mile, it is fortunate that injuries were few and slight. The severity of injuries from shattering glass is unpredictable. But for the holiday period, up to fifty people could have been employed in and about the depot and could have been at risk, though it can be argued that had the depot been occupied, any fire occurring would have been discovered at an earlier stage.

50 There can be little doubt that in the circumstances which occurred, the major risk to life was that to the firemen of Strathclyde Fire Brigade. If Renfrew Station personnel had not been attending another incident, it is likely that they would have been engaged in fire fighting operations when the explosion occurred.

Residual risk dealt with after the explosion

51 It is not proposed to deal in detail with the residual risks dealt with after the explosion but they do merit a mention. The first problem was to decide the extent of explosion and fire risk from sodium chlorate remaining in damaged drums or spilled on the ground over the large area indicated in Appendix 4 Fig 2. HM Explosives Inspectorate advised that, as the sodium chlorate might be contaminated with carbonaceous material, it should be kept wet and removed as soon as possible. It was thought that although some drums might not have split open significantly in the explosion, they might have dry contaminated contents, thus presenting an explosion risk with the danger of injury over a range of about 100 m if disturbed (Fig 8). Accordingly, attention was first given to the sodium chlorate, but in the event no undamaged drums or relatively undamaged drums were found and the collection and disposal of sodium chlorate was safely carried out over a period of a few weeks. The instability of parts of the damaged structure of Sheds A and C was appreciated to some extent at the outset, and persons entering the damaged buildings were restricted and wore safety helmets. When the exact extent of the instability of the sheds was determined all people were withdrawn from the vicinity until demolition contractors had stabilised the more dangerous parts of the buildings by temporary guying and removal of loose roof and wall sheets. There were a number of gas bottles in the buildings which had been involved in the fire. These involved oxygen, argon, carbon dioxide, propane, acetylene and air cylinders. The Regional Safety Officer of BOC Limited assisted in an evaluation of the dangers from these cylinders and they were removed for assessment of their safety. There were no gas mains on the premises and electrical isolation prior to demolition was no problem.

52 The site was contaminated with chrysotile asbestos containing waste from the burnt out roof and wall sheets, the bituminous coating of which contained asbestos. On 7 January a series of dust samples were taken along the sides of Sheds A and C at points where the asbestos



Fig 8 General view of the seat of the explosion with damaged drums of sodium chlorate in the foreground.

contamination appeared to be worst. The static atmospheric samples revealed concentrations of asbestos in the range of 0.6 to 1.2 fibres/ml which were within the current hygiene standard of 2.0 fibres/ml. On 10 January a series of personal samples were taken in the breathing zones of persons employed on the site, including those who were involved in clearing up asbestos contamination. These samples revealed asbestos dust levels in the region of 0.5 fibres/ml, again within the recognised hygiene standard. As demolition work proceeded it became necessary to fence off the entire contaminated area. Washing and changing facilities and appropriate protective clothing were necessary throughout the demolition operations, to comply with the Asbestos Regulations 1969; asbestos waste was disposed of in accordance with the requirements of the Control of Pollution Act 1974. The order of priority to deal with the various dangers and provide the necessary safeguards posed problems throughout the remedial work; these were resolved by co-ordination and supervision of the remedial work by the consultants and by the co-operation of people and officials concerned.

Legislation

53 The only premises at this depot which had been inspected by HM Factory Inspectorate was Shed C, which was a bonded warehouse registered in 1970 as a warehouse under Section 125 of the Factories Act 1961. The last visit to Shed C by the Inspectorate was in December 1974.

54 It is considered that Shed A, occupied and used for the business of storage, was a warehouse within the terms of Section 125 of the Factories Act 1961, but there is no requirement to notify HM Factory Inspectorate of such occupation. The fire precautions requirements in Part II of the Factories Act 1961, which were in force when the shed was occupied in 1976, did not apply to warehouses. Fire fighting extinguishers were provided at the premises which were subject in terms of the lease to inspection by fire officers of the Clyde Port Authority. The office in Shed A was subject to the requirements of the Offices, Shops and Railway Premises Act 1963, under which notification of occupation of office premises should have been sent to HM Factory Inspectorate, but this was not done. The mechanical repair to vehicles and trailers amounted to no more than running repairs and these activities were excluded from the requirements of the Factories Act 1961 by virtue of the provisions of Section 175(10).

55 The HSW Act 1974 has wide application. Section 2 provides, among other things, that it is the duty of every employer to make arrangements for ensuring, so far as is reasonably practicable, safety in connection with the storage of substances. Section 3 has the effect of extending this duty to provide comparable safety to members of the public.

56 In terms of Section 2(3) of the HSW Act 1974, James Kelman Transport and Storage had not, at the time of the incident, produced a written statement of

their general policy with respect to the health and safety at work of their employees.

Conclusions

57 The source of ignition for the fire on 4 January 1977 at the Braehead container depot was a fire started by children outside the shed occupied by James Kelman Transport and Storage.

58 The fire spread rapidly across the bituminous coatings of the corrugated steel sheets forming the shed's roof and walls. Molten bitumastic fell from the roof into the shed in which 67 tonnes of sodium chlorate (99% pure) were stored in 1774 steel drums. In the intense heat of the fire, a number of these drums exploded. As the incident occurred on a public holiday, shock or minor injuries were sustained by only twelve members of the public and a watchman; however two warehouses were wrecked and there was blast damage to property within a one mile radius.

59 Sodium chlorate has long been known as an oxidising agent and for its unpredictable behaviour when mixed with combustible contaminants. However, research after the Braehead incident disclosed that on at least six occasions since 1899 stores of potassium chlorate or sodium chlorate in an almost pure state have been implicated in explosions, most recently in a warehouse at Hamilton, Lanarkshire in 1969 and in a ship at Barcelona in 1974. In all cases the chemical was stored in drums or kegs within a building or ship. Trials by RLSB at Buxton and in East Anglia showed that while drums of sodium chlorate burned strongly when heated by a fire in the open, the small degree of confinement offered by a three sided roofed enclosure caused a fire to produce explosions among the drums.

60 The HSE have considered the legal implications, particularly under the HSW Act 1974, Section 2. Undoubtedly the storage of the sodium chlorate in a building clad with bitumenised corrugated steel sheets was unwise, as was its storage close to powdered milk which was a potential contaminant of the sodium chlorate and was itself a fire hazard, but it is considered that in the light of knowledge existing before the incident James Kelman Transport and Storage could not have foreseen the disastrous explosive potential of the material. All that could have been foreseen was a very large fire fuelled by the oxidising properties of the sodium chlorate, with perhaps some localised explosion potential from a sodium chlorate and powdered milk mixture, if the fire was unable to be controlled. An incident of this lesser scale was comparable with the fire that did occur in the adjacent bonded whisky warehouse in shed C. In these circumstances and taking into account the origin of the fire, the HSE decided not to take any further legal action.

61 Strathclyde police made a detailed enquiry and submitted a report to the Procurator Fiscal on possible legal action against the children involved in the initial

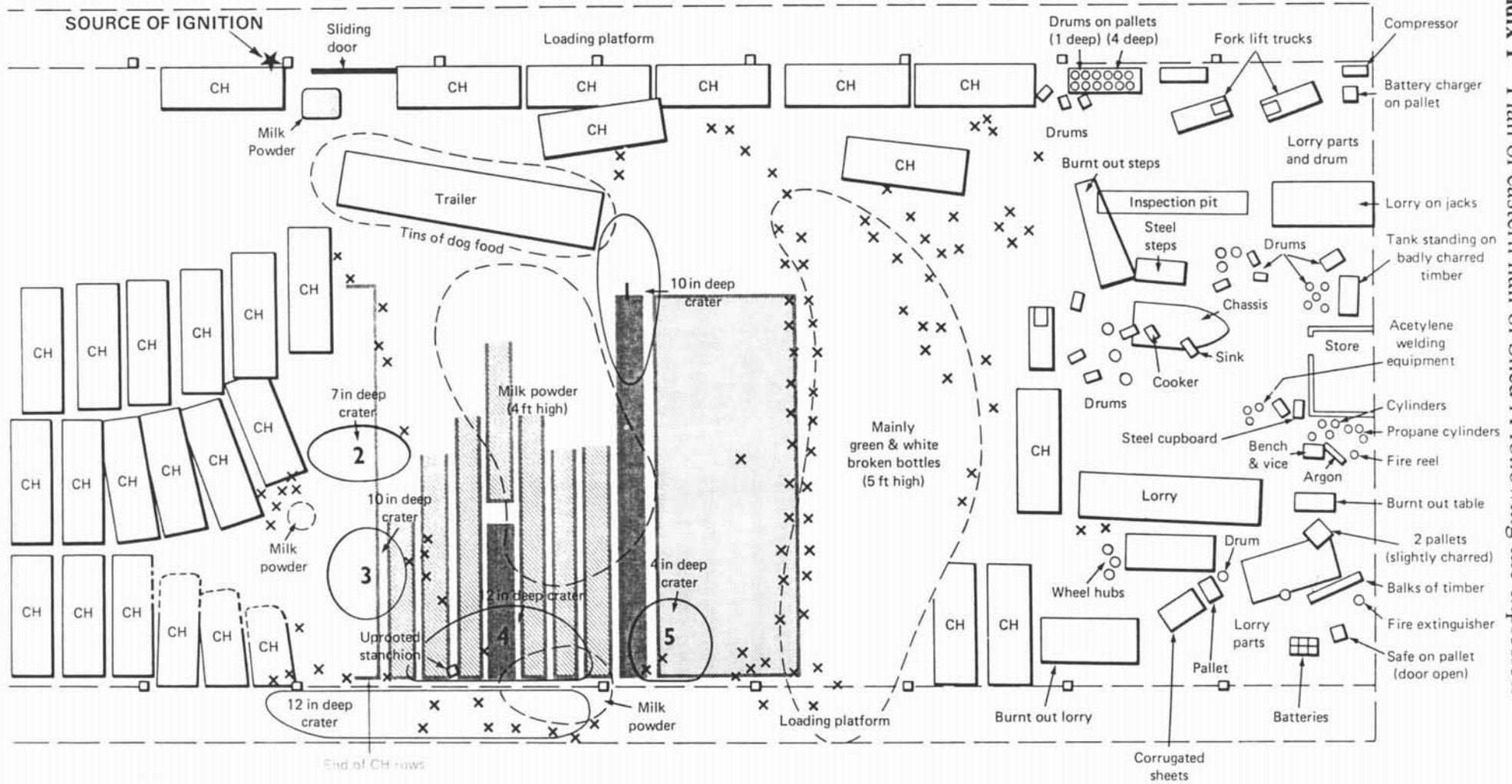
outbreak of fire but after due consideration it was decided that no further action should be taken against the children.

Recommendations

62 It is suggested that all bodies, national and international, concerned with legislation, codes of practice or advice on hazards and precautions relating to the storage, conveyance or handling of sodium chlorate should in the light of this report, reconsider the dangers and recommended precautions. In particular

- (a) Reclassification of sodium chlorate should be considered, since experiments have shown that it can explode under intense heat when packed in metal drums.
- (b) Consideration should be given to making the large scale storage of sodium chlorate subject to the same planning and safety procedures as other substances constituting a potential major hazard.*
- (c) Sodium chlorate should not be stored close to carbonaceous material or where it is liable to be subjected to intense heat. In practice, this means that bulk storage of sodium chlorate should be segregated in a suitable fire-resisting storeroom or in a separate building, constructed of non-combustible material.
- (d) Suitable precautions should also be taken for smaller quantities of sodium chlorate in the distribution chain.
- (e) The risk of spread of fire-danger in buildings of the type involved in the accident should be re-iterated with special emphasis on their unsuitability for storage of flammable or combustible materials.
- (f) To provide a greater understanding of the behaviour of sodium chlorate and similar materials under the intensive conditions which develop in actual fires, study and experiment should be conducted. This would assist the review and setting of suitable national, and ultimately international, standards for the storage and transport of such hazardous materials.

*Schedule 1 to the draft Hazardous Installations (Notification and Survey) Regulations now contains provision for sodium chlorate to be taken into account.



CH ... Combine harvester
 X ... Sodium chlorate drums

Scale: 25 ft

Appendix 2 The report of HM Inspector of Explosives

Explosions and craters

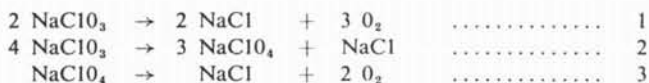
1 Witness evidence of the explosions indicated that there had been five separate incidents, described as two large explosions followed in rapid succession by three smaller ones. Examination of the warehouse after the incidents of 4 January 1977 showed that there were five craters, two large and three small. Subsequent enquiries showed that the position of the two larger craters, coincided with the position of stacked sodium chlorate prior to the incident. It was further established that the chlorate at the site of the principal craters had been surrounded either by stacked milk powder alone, or by milk powder on one side and glass bottles on the other. Finally it was established from evidence that the warehouse had been on fire for at least ten minutes prior to the explosions, and that the constructional characteristics of the warehouse would have meant that the fire was of an intense nature and widespread.

2 From the evidence summarised above, it can be seen that the sodium chlorate was at the source of the major explosions in the incident. The chlorate when stacked would have suffered significant confinement by surrounding stores. I contend that in this situation and subjected to intense heating, a portion of the sodium chlorate would have proceeded to detonation. It is significant that the centres of the two principal craters coincided with the ends of a row of stacked chlorate, ie that part of the stored chlorate which would have been heated most intensely by an adjacent fire. It is a matter of conjecture which principal explosion occurred first, the one adjacent to the south wall of the warehouse or the one towards the middle of the building. After a study of all the available evidence including the damage pattern, I would favour the first explosion occurring at the south wall, since this equates best with the subsequent distribution of scattered chlorate cans. It will be recognised that the first of these explosions would cause considerable disruption inside the warehouse, and could well have been instrumental in triggering the second. This would arise from the fact that chlorate is more susceptible to heat plus shock initiation than heat initiation alone. The three subsequent 'smaller' explosions could have been caused either by smaller scattered concentrations of drums being heated to detonation or more probably by localised mixtures of spilled chlorate and milk powder being initiated by fire.

The nature of sodium chlorate behaviour

3 Sodium chlorate, NaClO_3 , is an oxidiser that finds quite extensive use in matches, explosives, leather tanning, weed killing and bleaching. It is poisonous, melts at 249°C and liberates oxygen at 300°C . Decomposition starts at about 300°C , is exothermic and is self sustaining above a critical temperature ^(1,2). Chlorates tend to liberate oxygen explosively under influence of friction, shock, concussion, or heat at 400°C ⁽³⁾. According to Von Schwartz ⁽⁴⁾ "All these salts,

(chlorates) are highly explosive and dangerous". The reaction mechanisms of chlorates when heated by themselves are complex and many points regarding the decomposition of the dry salts at elevated temperatures in the pure state, and in the presence of catalytically acting agents are still not fully understood ⁽⁶⁾. Reactions which are generally recognised to take part in the decomposition are:



4 It is claimed that the chlorite form (NaClO_2) also occurs as an intermediate in the uncatalysed decomposition ⁽⁶⁾. Also, possible ⁽⁷⁾ is:



which might suggest:



as a possibility. Metal oxides act as catalysts to reaction 1 by lowering the effective decomposition temperature, and since NaCl is a catalyst to disproportionation, reaction 2 is autocatalytic.

5 Many other substances catalyse the thermal decomposition of sodium chlorate and some form explosive mixtures. Such mixtures, particularly those involving organic materials, e.g. sugars, sawdust, oils etc, or with inorganic materials such as sulphur, finely divided metals, acids, etc, may be extremely sensitive to shock friction or heat, and can burn or explode spontaneously ^(1, 2). The readiness with which chlorates and organic and oxidisable matter react by friction or moderate heating renders careful packing and handling in transit essential. It is also very important to guard against spillages, as chlorate being a white crystalline powder, is not particularly distinctive. Sweeping of such spillings with dust, fluff etc may form a very hazardous mixture, and explosions have been known to occur from potassium chlorate becoming accidentally mixed with sugar ⁽⁵⁾.

The mechanisms for explosion

6 In the light of the properties of sodium chlorate mentioned above, we have a situation where four hypotheses are possible to explain what happened in the Renfrew warehouse:

- (a) One or more drums of sodium chlorate burst due to the internal pressure created by thermal decomposition, ejecting the contents which then became mixed with the adjacent finely divided milk powder, this mixture then exploding under the influence of the fire, *or*
- (b) One or more drums of sodium chlorate burst or blew off its lid due to the internal pressure created by the thermal decomposition, exposing the contents which then became mixed with the dripping bitumastic

melted from the warehouse walls and roof, the mixture then exploding under the influence of the fire, *or*

- (c) A detonable mixture of sodium chlorate and melted polythene drum liner was created inside several drums and subsequently exploded as a result of the heat of the fire, *or*
- (d) Drums of sodium chlorate exposed to an intense fire condition proceeded to an explosive decomposition (i.e. no fuel involved in the reaction).

7 What cannot be denied is that five explosions occurred in the warehouse, and that two of them were relatively powerful. My estimates based on the effects of the explosions, suggest that an explosive equivalent to about 225 kg (500 lb) of TNT was involved, with the major explosions being of the order of 90 kg (200 lb) TNT equivalent each. Thus with typical chlorate explosive, oxidiser to fuel ratio of 80:20 we are looking for about 36 kg (80 lb) of fuel additive if we assume the 2:1 power ratio between TNT and chlorate-type explosives which is suggested in the literature.

8 Under hypothesis (a) this amount of fuel could possibly be available although of course we would be looking for a mix of 145 kg (320 lb) chlorate with 36 kg (80 lb) fuel i.e. the contents of about three of the 50 kg drums would have to be ejected and mixed with the milk powder at about the same time. This does not appear very likely, particularly when a similar order of mix would have been required within seconds to produce the second explosion. Also, against hypothesis (a) is the fact that the principal explosion craters were situated within the chlorate storage area and not within the milk storage area, i.e. requiring that the milk powder was ejected into the chlorate rather than vice versa.

9 For hypothesis (b) approximately similar levels of fuel would be required to produce explosions of the severity estimated. In this instance we are looking for multiple lid-ejections exposing contents (top rows of stacks only?) and being fed with a virtual 'waterfall' of melted bitumastic from the warehouse walls and roof. Also if this were the mechanism of the principal explosions they would have occurred at the top of the stacks of chlorate, and would not therefore have produced ground craters. I think this hypothesis would have been a much more viable explanation for a large number of smaller explosions which occurred without cratering effects.

10 Under hypothesis (c) we again require a similar quantity of fuel for the principal explosions. However, in this instance the fuel is the polythene drum liner, each weighing approximately 100 g. Thus each drum would have an explosive equivalent of approx 250 g of TNT (say 0.5 lb), therefore 400 drums would have been required to take part in the first explosion. This is not impossible, but it does seem somewhat unlikely.

11 At first sight the energy available for hypothesis (d) is not very great, the conversion according to equation 1

above being:



for which the exotherm is variously quoted as 100 to 150 calories per gram, i.e. at best about one-seventh the energy of TNT. However, whether or not this is all that happens in the thermal decomposition of sodium chlorate, or whether reactions 5 and 6 above for example, contribute to the explosive power is open to debate. What is recognised is that an alkali-chlorate in its pure state, will explode if heated with sufficient intensity and speed^(9, 9, 10), albeit with relatively low power. Nevertheless if we reckon on one-seventh TNT rating, we get for the first explosion:

- (i) estimated TNT equivalent = 90 kg (200 lb)
- (ii) sodium chlorate decomposition required = $7 \times 90 = 630$ kg (1400 lb)

i.e. approximately fourteen drums of chlorate. This number of drums is more realistic, and can be visualised at the end of a stacked row, having arrangement nine drums per pallet, four pallets high, one pallet wide.

12 However, under each of the above considerations it must be concluded that significant modification of scale and effect would occur if:

- (i) for hypotheses (a), (b), (c), (d) the explosion of one drum of chlorate communicated to others which then exploded in sympathy;

or

- (ii) for hypothesis (c) the 0.23 kg (0.5 lb) TNT equivalent explosion in a drum of chlorate acted as a priming charge for the whole of the drum contents (i.e. one drum would then have a yield of about 6.4 kg (14 lb) of TNT).

13 The likelihood of these secondary effects is unknown, and would require considerable research effort to elucidate. A certain degree of communication might be expected, especially if drums in receipt of an explosive shock wave were themselves teetering on the brink of an explosive decomposition.

14 Of the various ideas available to explain the chlorate explosions, I favour hypothesis (d) coveting explosive decomposition as the cause of the Renfrew explosions. Thus, despite the fact that there was so much milk powder adjacent to the chlorate, and hence so much possible fuel, I do not think that the milk powder participated in the principal explosives which were the cause of all the damage in the incident.

Evidence from previous events

15 In support of the above idea I have found reference to several previous events of similar nature. These events either involved potassium or sodium chlorate and in each violent explosion was preceded by an intense fire.

16 In 1899 at St Helens in Lancashire wooden kegs of potassium chlorate were being off loaded from a lorry adjacent to a storehouse containing 156 t of chlorate. There was an ignition on the loading platform and fire

spread rapidly into the store. After about ten minutes of intense fire in the store, there was a tremendous explosion which shook the whole town killing five people and injuring over forty others. It was found that the explosion had occurred among the chlorate and had left a crater about 3 ft deep, resulting from the explosive decomposition of about 5 t of the material. ⁽¹¹⁾

17 In 1908 at Manchester a store caught fire in similar circumstances to those described above. On this occasion the store contained 12 t of potassium chlorate 32 t of sodium chlorate and 1.5 t of barium chlorate, loaded in wooden casks lined with stout blue paper. A series of three explosions occurred about five minutes after commencement of the fire. ⁽¹²⁾

18 In 1910 there was a fire in a store shed at Liverpool. The shed contained 20 t of potassium chlorate. After the fire had been burning fiercely for a few minutes, an explosion of some violence occurred, wrecking the building and breaking nearly all the windows in the neighbourhood, including window frames in some cases. ⁽¹³⁾

19 In 1947 in Poplar, E London, a Thames barge loaded with 40 t of sodium chlorate, half contained in wooden casks and half in steel drums, went on fire, when adjacent to an unloading wharf. After a few minutes of intense burning there were three larger explosions, followed a short time later by a further two explosions. The barge was a complete wreck. Adjoining buildings had their windows blown out and casks of the material were found burning on the tops of buildings some 200 yd away. ⁽¹⁴⁾

20 In 1969, in Hamilton, Scotland, a store containing approximately 20 t of sodium chlorate was destroyed. Sparks and hot metal from oxy-propane cutting equipment working on the roof, dropped on to and ignited timber pallets loaded with wooden casks of chlorate, causing a serious fire, attended by explosions. The store was completely disintegrated. An adjoining store which also contained a large quantity of sodium chlorate in steel drums and wooden casks, also went on fire and again there were several explosions. Debris was scattered over a large area and was found more than half a mile away. 190 houses on a nearby estate were damaged. ⁽¹⁵⁾

21 Finally, in 1974 a general cargo ship caught fire while loading at a quay in Barcelona. Fire spread throughout the vessel and eventually reached a hold containing 3700 drums of potassium chlorate. Some time later a very violent explosion occurred in the hold, throwing drums of potassium chlorate all over the dock area. One of the heavy hatch beams was sent a distance of 50 m and one of the cargo winches was hurled onto the dockside. The explosion damaged the hull plating of the ship causing a list. The ship later sank alongside the dock. ⁽¹⁶⁾

22 Thus we have a series of incidents where chlorate involved in an intense fire has exploded. I consider that this behaviour is not dependent upon the expeditious

mixing of possible organic fuels with the chlorate oxidiser as often suspected, but is more associated with the basic performance of the materials under severe conditions of thermal decomposition.

Evidence from bonfire tests

23 In pursuit of evidence on the behaviour of sodium chlorate in fire, I asked RARDE Woolwich/RLSD Buxton to conduct a series of bonfire tests. In these tests drums of sodium chlorate purchased from the Strathclyde Chemical Co Ltd, the owners of the material in the Renfrew warehouse, were placed inside bonfires, and their performance monitored. The following results were obtained from a series of trials held at RLSD Buxton:

(a) Fire 1	One drum placed in standard bonfire.	Lid blown off drum during test otherwise negative result.
(b) Fire 2	One drum placed in bonfire, and 50 kg of loose chlorate emptied into the fire prior to ignition in an attempt to increase fire intensity.	Apart from an intensive burn there was a negative result.
(c) Fire 3	A double size bonfire was built surround three 50 kg drums of chlorate. The centre drum was 'as received' and above it was placed a drum of sand to aid confinement. A 50 kg drum was placed on either side of the centre drum and each punctured, with the holes facing the centre drum in an attempt to gain flame impingement. As in the second fire 50 kg of loose chlorate was spread in the fire prior to ignition.	There was a very intensive burning of the fire with brilliant white radiation, and audible jetting noises from impinging flames. Apart from a few cracks and bags there were no explosions of the chlorate. The centre drum was totally consumed by the fire.

24 Following a study of the evidence from the above fires together with a reconsideration of the various incidents presented in the section above, I asked for a further bonfire test. This test was to simulate a stack of sodium chlorate under mild confinement as might exist in a warehouse. It appeared to me that all explosions involving chlorate had been in warehouses, storerooms, ships holds etc, where heat generated in the fire would not easily escape, whereas an open air bonfire would lose much of its heat rapidly to the atmosphere and thus perhaps fail to achieve the critical heat input condition I was stalking. After some organisational difficulties, RARDE Woolwich were able to conduct such a bonfire at a MOD test range in Suffolk:

(d) Fire 4	A stack of 36 x 25 kg cans of chlorate formed the centre piece of a large bonfire, built inside a three sided roofed enclosure. Again loose chlorate was poured into the fire prior to ignition to increase fire intensity.	6½ minutes after ignition, and 1½ minutes after the intensity associated with the involvement of the loose chlorate had commended, an explosion occurred followed seconds later by a second. Pieces of drum were hurled 36 ft out from the fire, and blast gauges placed at 20 ft distance were uprooted.
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25 It will be apparent that the behaviour of sodium chlorate in the test bonfires, is consistent with hypothesis

(d) presented above, since there was no milk powder or dripping bitumastic involved in any of the fires (hypotheses (a) and (b)), while if hypothesis (c) were correct, some explosive reaction might have been expected from Fires 1, 2 or 3.

Implications of the Renfrew event

26 General literature, manufacturers pamphlets and fire authority classifications for sodium chlorate, place it among the less reactive oxidisers. For example the American codes issued by NFPA, place it in Class I which they define as “an oxidising material whose primary hazard is that it may increase the burning rate of combustible material with which it comes into contact” (17). It is not until Class 4 is reached that chemicals that “can undergo an explosive reaction when catalysed or exposed to heat, shock or friction”, are listed. Similarly the British Fire Protection Association only say that “Containers may explode when involved in a fire” (18). Their information sheet does not expand on the possible explosive effects or indicate that events such as occurred at Renfrew may be possible.

27 It cannot be said at this stage what the correct classification for sodium chlorate should be. However the classification should be reconsidered in the light of the evidence presented above. Similarly, the HSE Policy Branches should give cognisance to the above evidence when they come to review the various standards that apply to the storage and transport of hazardous materials generally, and of sodium chlorate in particular.

Finally, in order to provide a scientific framework for the greater understanding of the behaviour of sodium

chlorate and similar materials under intense fire conditions, it is recommended that further study and experiment be conducted on the subject.

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- 15 Research Report on Fire at Hamilton on 19 March 1969 – Lanarkshire Fire Brigade.
- 16 Incident report received from Dr P V Rutledge of Dr J H Burgoyne and Partners following discussions on the explosive behaviour of alkali chlorates in fire situations.
- 17 Code for the storage of liquid and solid oxidising materials. National Fire Protection Agency (NFPA) No. 43A 1974.
- 18 FPA Information Sheet H7 October 1972 – Sodium Chlorate.

Appendix 3 Braehead container depot fire and explosion specification and analysis of the sodium chlorate

(a) Specification (supplied by the owners, the Strathclyde Chemical Co Ltd, Beith Road, Johnstone, Renfrewshire)

Sodium chlorate	99.00%
Sodium chloride	0.10%
Sodium bromate	0.05%
Insolubles	0.05%

Water	0.05%
Free running agent (either sodium carbonate or magnesium oxide)	0.75%

(b) Analysis (made by the Occupational Hygiene Laboratory of the Health and Safety Executive)

Sample	Chlorate as sodium chlorate (a)	Chloride as sodium chloride (a)	Perchlorate as sodium perchlorate (a)	Loss on drying (a)	Chromium (b)	Iron (b)	Manganese (b)
From inside shed A exposed to fire	93.2	0.38	<1	8.2	4	20	3
From tin of material collected away from shed A	90	—	<0.5	—	30	50	3

(a) Expressed as % W/W on original as received sample.
 (b) Expressed as parts per million of dried sample.

X-ray fluorescence also detected the presence of sodium, chlorine, oxygen and bromine, with traces of iron, potassium and magnesium.

Appendix 4 A damage survey in the far field by H Phillips, DSc, C Eng, MI Mech E

Introduction

1 On 8 and 9 January 1977 I supervised the making of a damage survey in the area around the damaged warehouse at Braehead Container Clearance Depot; this survey was made at the request of HM Superintending Specialist Inspector of Factories.

2 The survey was carried out by myself and four members (two scientists and two photographers) of the staff of the HSE on my instructions and under my general supervision. We inspected the damaged warehouses, but the survey itself was made in the surrounding area where the type of damage could be related to overpressures due to blast, and with the intention of estimating the 'TNT equivalent' of the explosion.

Damage survey

3 The damage observed outside the warehouses ranged from transport containers with their sides buckled in, to occasional breakage of shop windows. Other damage was observed at the site but much of it could not be used in estimating the size of the explosion and is not reported here. Craven (Blast damage, Conference on Safety in the Chemical Industry: Hazard Evaluation and Plant Protection, UMIST 1976) provided an extensive list of the blast overpressures required to cause structural damage, and, in general, only damage which could be described in the terms that Craven used was of any value in the determination of blast overpressures at Braehead. Much of the damage could not be described in these terms; for example the power station suffered extensive breakage of window glass, but most of this glass was thicker than normal, or wire reinforced. Craven's description of window damage related to the type of glazing used in domestic premises.

4 From the overpressures estimated from the damage survey, the TNT equivalent was found from the graphs given by Brasie and Simpson (Guidelines for estimating damage from chemical explosions. Symposium on Loss Prevention in the Process Industries, 1968).

5 The warehouses were situated in the centre of open terrain. The nearest buildings where damage might have been observed were:

- (a) The power station. The nearest point of the power station was 162 m (530 ft) from the assumed centre of the explosion.
- (b) Renfrew Burgh. The nearest domestic dwellings were 457 m (1500 ft) from the centre of the explosion.
- (c) Dwellings on the north bank of the Clyde were 762 m (2500 ft) from the centre of the explosion.

6 Therefore I confined my attention to noting blast damage in the power station, in Renfrew Burgh, and to the containers which were between the site of the explosion and the power station.

7 On 8 January, when I looked for evidence of window damage, almost all of the damage to domestic property

had been repaired. The evidence I had to use was indirect, i.e. I observed piles of broken glass below the window, and window-panes with new putty.

8 Use was made of the following observations of damage:

- (a) An occasional broken window in Paisley Road, a broken door frame in the Police Station. (Area 1 of Fig 1).
Overpressures 0.3 kPa (0.05 psi) at a radius of 1067 m (3500 ft) giving a TNT equivalent of 304 kg (670 lb).
- (b) More extensive glass breakage at the Town Hall and in shops and flats in Hairst St and Canal St. (Area 2 of Fig 1). Probably about 5 to 10% of glass broken. Overpressure, 1.0 kPa (0.15 psi) at a radius of 762 m (2500 ft) giving a TNT equivalent of 885 kg (1950 lb).
- (c) Extensive glass breakage in High Street, almost complete breakage of domestic glass in flats adjoining Charles St. (Area 3 of Fig 1).
Overpressure, 2.0 kPa (0.3 psi) at a radius of 152 m (500 ft) giving a TNT equivalent of 454 kg (1000 lb).
- (d) Asbestos wall panels removed by the blast from buildings adjoining the power station. (Area 4 of Fig 1).
Overpressure, 6.9 kPa (1.0 psi) at a radius of 275 m (900 ft) giving a TNT equivalent of 840 kg (1850 lb).
- (e) Slight structural damage to an internal brick wall in a building adjoining the Power Station. Cracked ceilings in the same building. (Area 5 of Fig 1).
Overpressure, 11.7 kPa (1.7 psi) at a radius of 152 m (500 ft) giving a TNT equivalent of 454 kg (1000 lb).
- (f) Sides of transport containers buckled (Figs 3 and 4) (Site 6 of Fig 1).
Overpressure, 34.5 kPa (5 psi) at a radius of 55 m (180 ft) giving a TNT equivalent of 785 kg (1730 lb).

9 The transport container damage does not appear in Craven's evaluation of the overpressures required to cause damage, but the overpressure was assessed in the following manner.

10 The increase in pressure outside the container had crushed the container and bent and broken the reinforcing frame. The volume within the framework had been reduced by about 10%. A factor of 3 was incorporated to compensate for:

- (a) insufficient time for the structure to respond fully to the short duration positive pressure pulse, and
- (b) some attempt to revert to the original volume when the positive pressure pulse was replaced by a negative wave.

11 This factor leads to a possible maximum reduction in volume by about 30%, which is equivalent to subjecting the container externally to a 34 kPa (5 psi) peak overpressure.

Assessment

12 The first estimate, at 8(a) could have been low due to:

- (a) freak damage; the broken windows being much larger than normal, or under some strain before the explosion, or being subjected to local untypical concentrations of blast overpressure.
- (b) the windows being within a surface boundary layer which was thickened by the presence of buildings between the 1067 m (3500 ft) radius and the explosion centre.

13 The estimate at 8(e) is not reliable because damage was to an internal 4.5 in brick wall, whereas Craven's blast data refers to the external walls of domestic premises.

14 The mean value of the remaining estimates is (820 kg) 1800 lb of TNT.

15 The TNT equivalents were deduced from the blast damage using the data of Brasie and Simpson, who plot blast overpressure (psi) against a scaled radius, $(ft/Q^{1/3})$ where Q is the weight of TNT in pounds. Craven also produces a curve of blast damage on the same co-ordinates but the use of Craven's data leads to a TNT equivalent of 5 tons. Strehlow and Baker (*The Characterisation and Evaluation of accidental explosions; Energy Combustion Sci.* 1976, *Prog.* 2, 27–60) point out the discrepancy between various curves for estimating TNT equivalents. They produce ten such curves, and at the level of 10.1 kPa (1.5 psi) blast overpressure the estimates of TNT equivalents vary by a factor of 6.5.

16 I consider that the use of Brasie and Simpson's data is to be preferred, because this has been the basis for estimation of TNT equivalent in other post-explosion studies, e.g. Flixborough, and the use of the same method of assessment at least allows comparisons to be made.

Missiles

17 HM Principal Inspector of Factories, supplied me with information on the area in which drums that contained, or had contained, sodium chlorate were found after the explosion. At the time of my inspection of the site the drums had been removed. The limit of distribution of the tins is marked in Fig 1, based on the information supplied, and a more detailed plan of this information appears in Fig 2.

18 It is generally assumed (see Craven) that debris will be confined within the radius at which explosion pressure is 2.0 kPa (0.3 psi). The chlorate drums, and most of the other debris (such as roofing sheets and timber from pallets) were within this radius. Asbestos fragments were projected further; possibly their flight was aided by their flat shape.

19 The only other significant projectile was a piece of rolled steel angle, 0.25 × 0.25 × 9 ft long which had been found on the power station roof.

Plan of warehouse

20 At the request of HM Principal Inspector of Factories we recorded the location of the contents of that part of one of the warehouses (Shed A) close to the centre of the explosion. The resulting plan is appended at Fig 5.

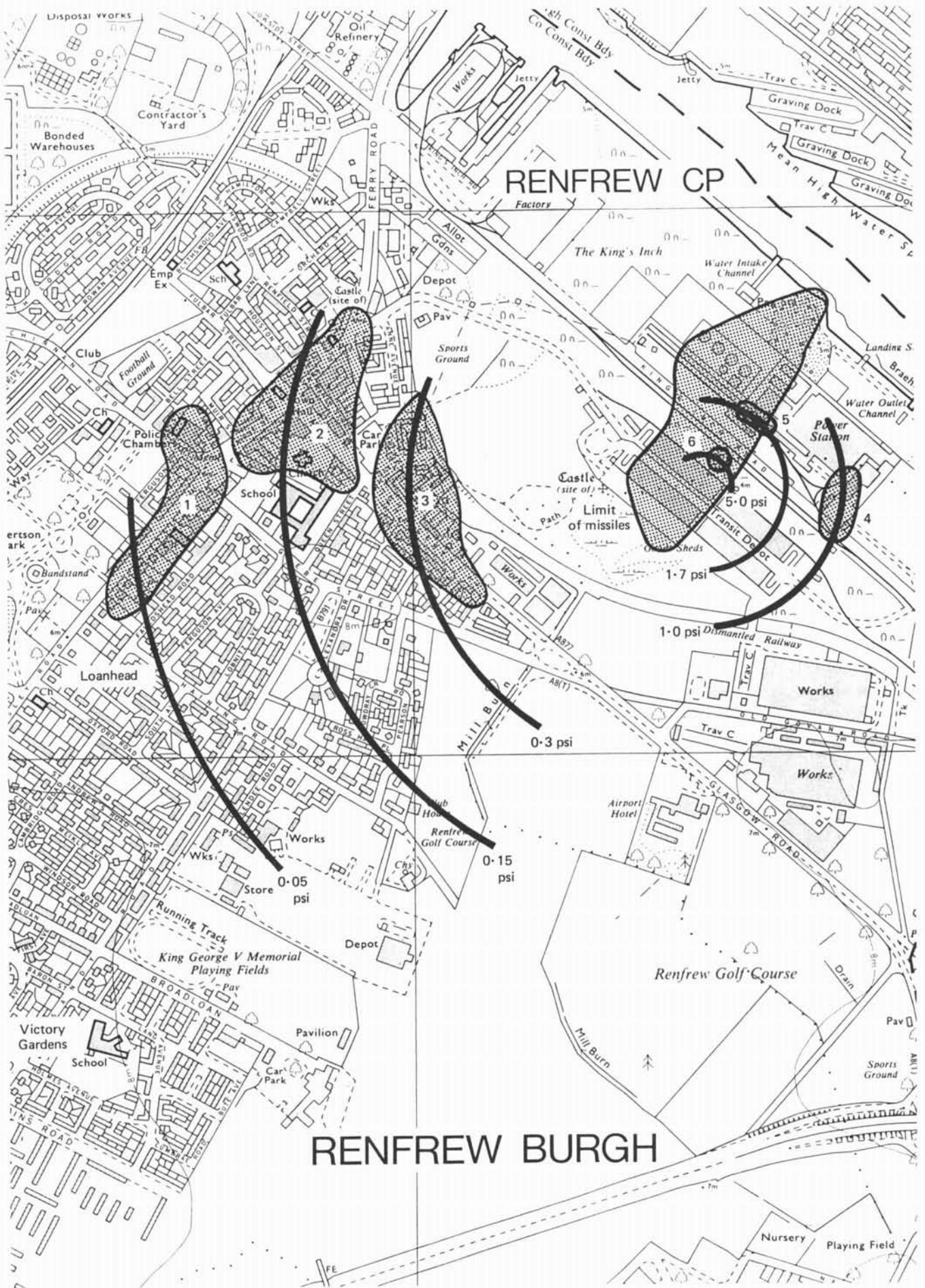


Fig 1 Area of damage survey.

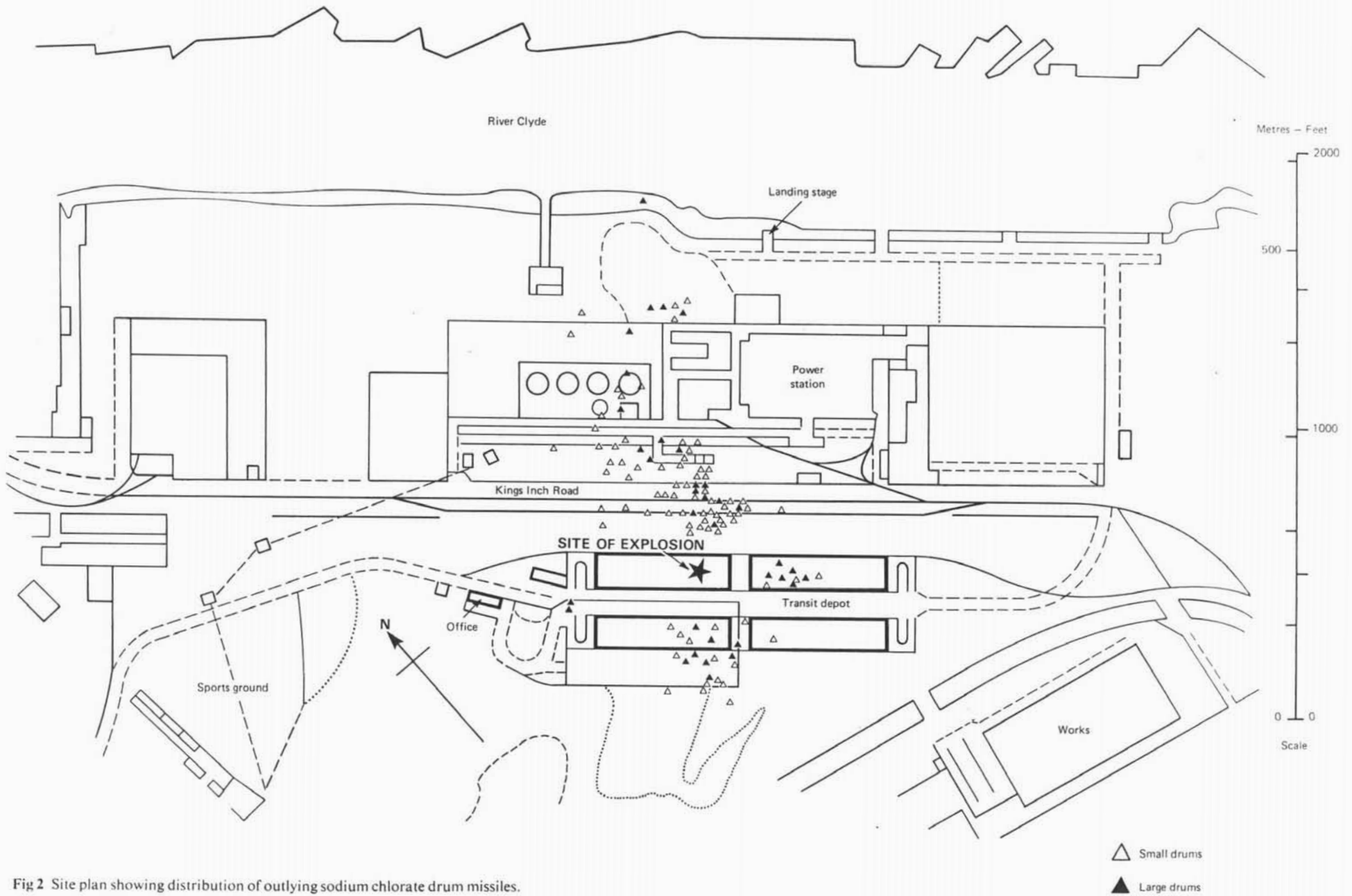


Fig 2 Site plan showing distribution of outlying sodium chlorate drum missiles.



Fig 3 Container.

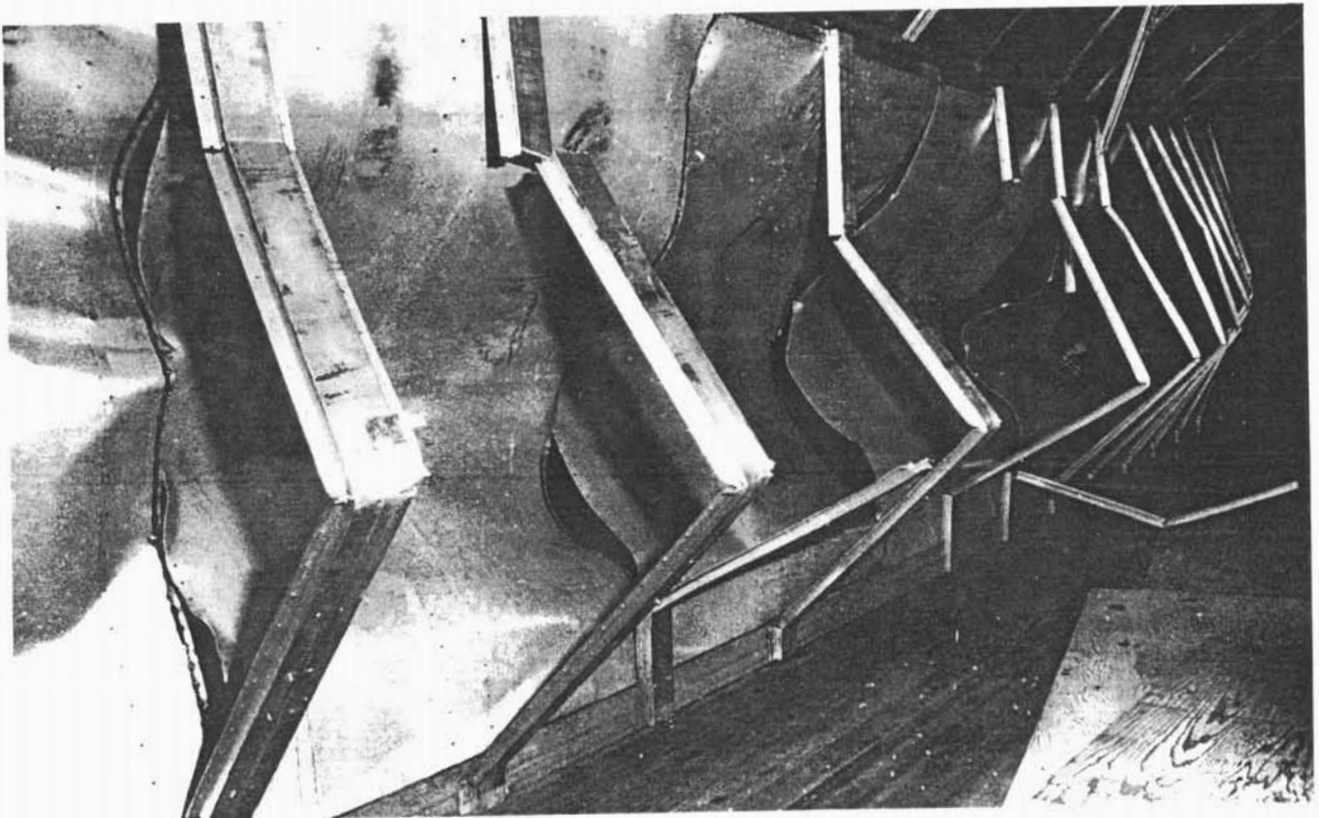


Fig 4 Interior of container.

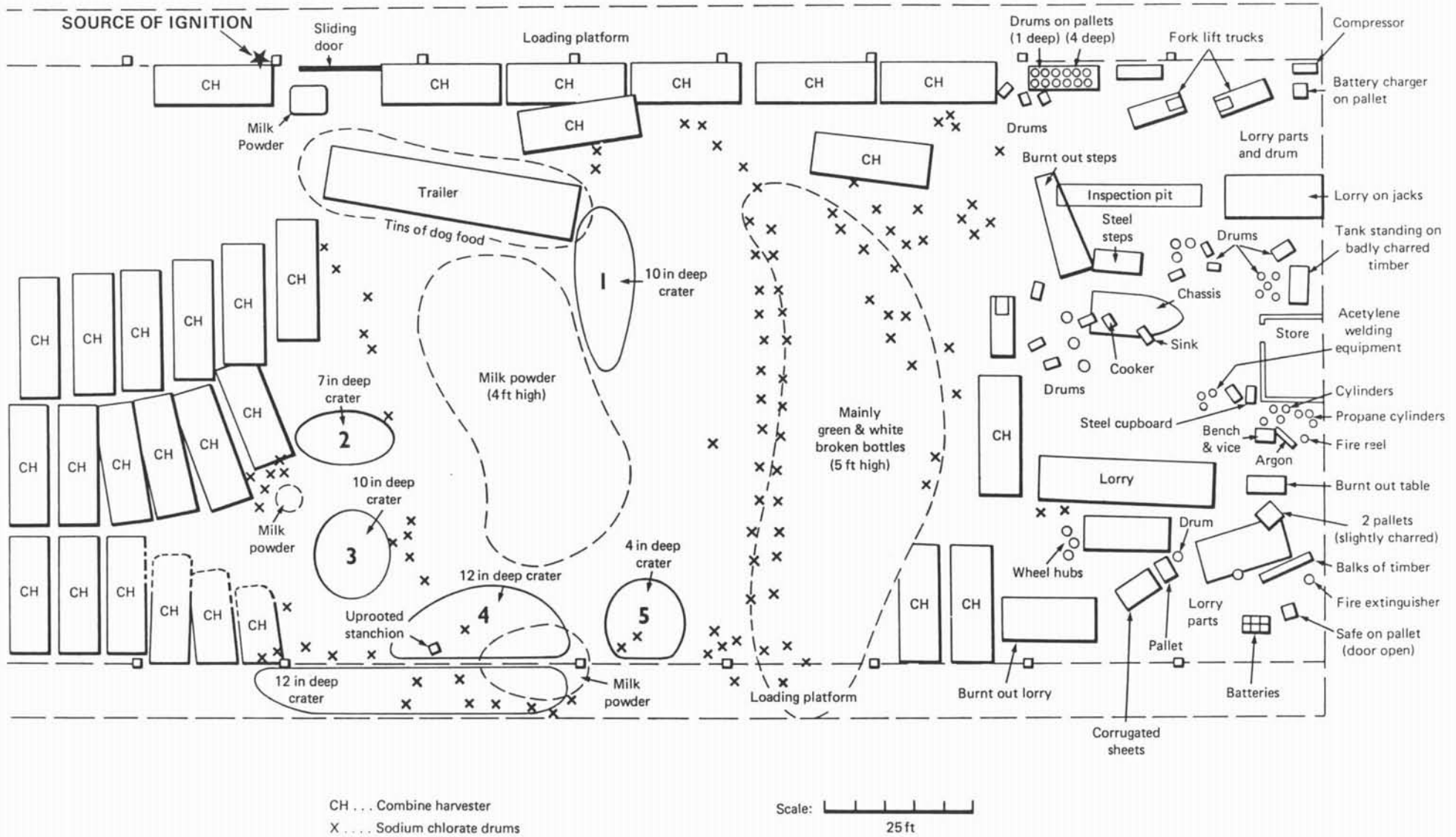


Fig 5 Plan of Shed A close to centre of explosion.