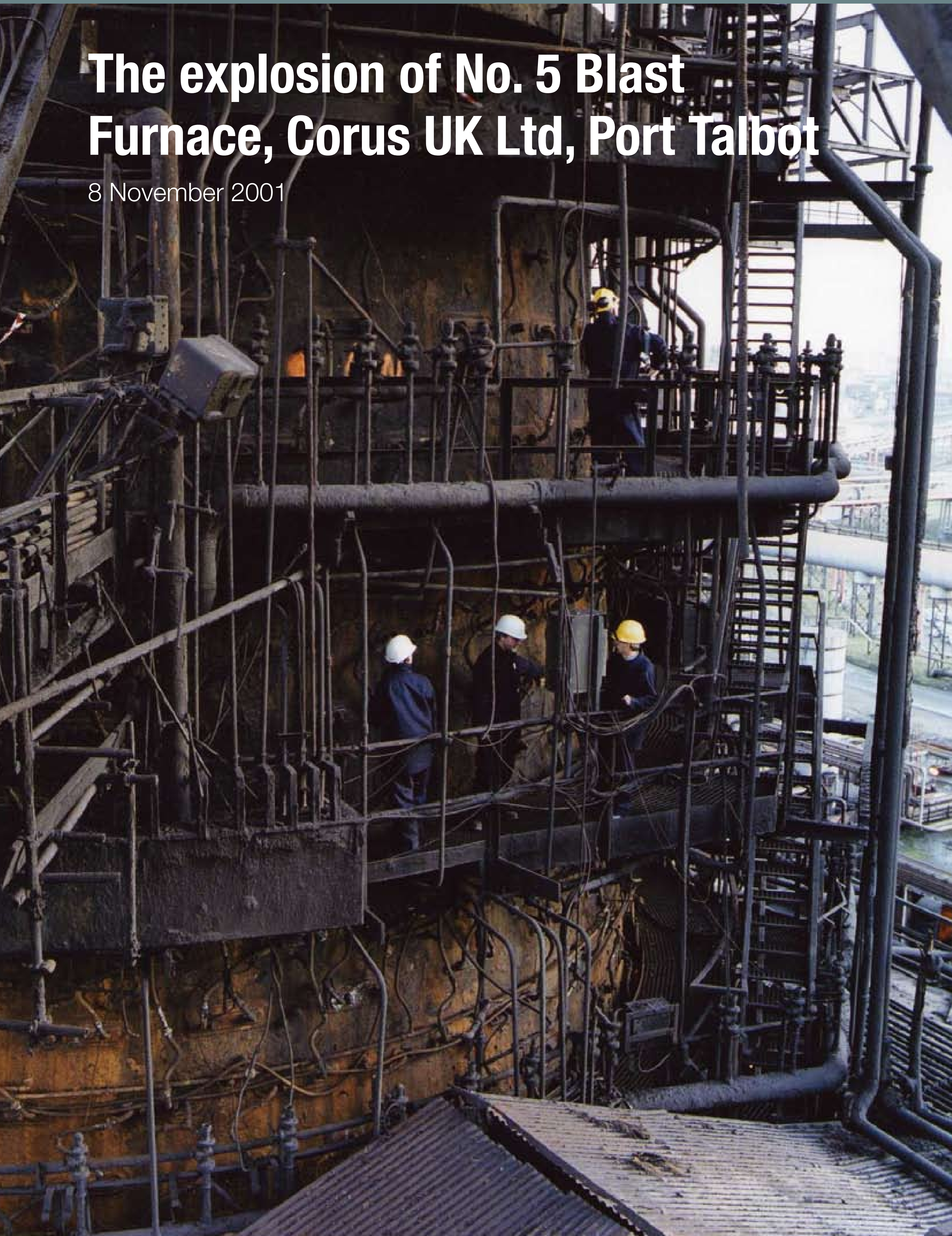
HSE

Health and Safety Executive

The explosion of No. 5 Blast Furnace, Corus UK Ltd, Port Talbot

8 November 2001



Contents

Introduction

1 This report concerns the events of 8 November 2001 at the premises of Corus UK Ltd, Port Talbot, South Wales. The explosion of one of the company's blast furnaces led to the tragic deaths of three employees and injury of a number of other people. The explosion caused widespread alarm and concern throughout the locality.

2 This is an account of the events leading to the explosion; the incident itself; the investigations and legal processes after the investigations; and the lessons to be learned. The lessons are there for the steel-making industry both in the UK and worldwide, but they contain many fundamental truths for all manufacturing industries.

Executive summary

The event

3 At the premises of Corus UK Ltd, Port Talbot, No. 5 Blast Furnace exploded at approximately 17.13 pm on 8 November 2001. The entire furnace, which with its contents weighed approximately 5000 tonnes, lifted bodily at the lap joint, rising some 0.75 m from its supporting structures, leading to the explosive release of hot materials (an estimated 200 tonnes in total, comprising largely solids and semi-solids, with a little molten metal) and gases into the cast house. Three employees died: Andrew Hutin, Stephen Galsworthy and Len Radford. A further 12 employees and contractors sustained severe injuries. Many more suffered minor injuries and shock.

4 The outcome of the explosion was unprecedented in the steel-making industry, but was the result of many failings in safety management by the company over an extended period. The explosion occurred after a prolonged attempt – over two days – to recover the furnace from a chilled-hearth situation caused by cooling water ingress. The immediate cause was the mixing of water and hot materials within the lower part of the furnace; the precise mechanism remains a matter that is not fully resolved.

5 The event attracted considerable public attention locally, nationally, and internationally within the wider steel-making industry.

6 The company was subsequently prosecuted under sections 2(1) and 3(1) of the Health and Safety at Work etc Act 1974 and was fined £1.33 million in the Crown Court, with £1.74 million costs also being awarded.

The cause

7 The immediate cause of the explosion was water and hot molten materials mixing within the lower part of the furnace vessel.

8 The water had entered the furnace from its cooling system following a chain of events initiated by the failure of safety-critical water cooling systems. At the time of the explosion, attempts were continuing to rectify the abnormal operating conditions that this had created and to recover the furnace.

9 The precursors to the explosion were a combination of significant failures in health and safety management extending over many years. These failures were not confined solely to the blast furnace plant; they extended elsewhere within the company, and in particular to the Energy Department which supplied essential cooling water for the furnace.

10 A failure to carry out suitable and sufficient risk assessments for blast furnace operations resulted in the failure to implement robust technical and procedural controls. There was insufficient redundancy and security of cooling water supplies, and overall cooling system reliability showed a downward and deteriorating trend over several months.

The investigation

11 A joint investigation was carried out by South Wales Police and the Health and Safety Executive (HSE) under the Work-Related Deaths Protocol. The Police held primacy for the first eight months. There was significant input from HSE specialist inspectors, the Health and Safety Laboratory (HSL), and South Wales Police forensic science teams. The Crown Prosecution Service was extensively involved in the various stages of the investigation; primacy passed to HSE following the decision that charges of manslaughter would not be brought against any party.

Lessons

12 The investigation identified a number of learning points for both Corus UK Ltd and its blast furnace operations, the wider steel industry, and other manufacturers. These have already been communicated to Corus UK Ltd and action has followed to secure the necessary improvements. Details of the actions taken by Corus UK Ltd are included later in this report. (*Lessons 1, 5, 9, 10, 14, 15 and 18 relate specifically to Corus UK Ltd and its blast furnace operations, although some will also have relevance for the wider steel industry. The remaining lessons all have even wider application.)

13 The lessons below are presented as a summary; they include both procedural, engineering, human factors and reliability issues. The basis for each lesson is explored later in this report.

14 The technical sections of this report should be read with reference to the appendices.

Safety management

Lesson 1 The company should review the role and function of the Safety Department. It should be better integrated into operational and engineering management.

Lesson 2 Blast furnaces are now under the COMAH regime (Control of Major Accident Hazards Regulations 1999), where identification and evaluation of major hazards is a legal requirement. Before this, predictive tools and techniques have had relatively limited use within the steel industry. Predictive tools for the assessment and management of risk should receive greater use within the steel industry and other process industries: eg Hazard and Operability Studies (HAZOPS), Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Process Hazard Review (PHR) and Layers of Protection Analysis (LoPA).

Cooling water

Lesson 3 Sufficient cooling water for furnaces should be available at all times; the supply systems should have an adequate level of reliability built into the system. This reliability should be brought about by good engineering design (including an adequate level of redundancy) and suitable maintenance, and should be monitored to indicate any threats to its integrity.

Lesson 4 Reliability engineering techniques should be employed to identify safety-critical plant and appropriate safeguards should be developed from these studies.

Lesson 5 Closed systems for furnace cooling water, or systems with equal or better reliability, should be provided wherever reasonably practicable.

Leak detection

Lesson 6 Speed in locating furnace cooling water leaks is essential. Rapid leak detection relies on good engineering, adequate detection protocols and suitably trained and competent operators. All operators of water-cooled furnaces should ensure that there are adequate measures in place for prompt leak detection.

Lesson 7 On water-cooled metallurgical furnaces, where it is reasonably practicable, appropriate instrumentation, specifically designed for leak identification, should be installed to give earlier and more precise detection of leaking cooler elements.

Maintenance

Lesson 8 Maintenance, inspection and, where appropriate, testing of plant and equipment associated with the reliable delivery of water to furnaces should be paramount. The potential effects of lack of maintenance, inspection and testing in terms of safety should be clearly understood. There should be adequate prior communication between works departments when any maintenance or other work that may potentially affect safe plant operation or reliability is proposed. Formal protocols should be considered for this. Safety-critical items should be identified and protocols and priorities established for their maintenance, inspection and testing.

Blast furnace recovery and abnormal plant conditions

Lesson 9 The specific process of conducting a blast furnace recovery gives rise to additional risks significantly over and above normal operational risks. It is essential that all personnel involved are aware of those risks and there are control measures, including arrangements for effective communication, in place such that adequate risk control is maintained.

Lesson 10 A specific issue with the recovery of No. 5 Blast Furnace was that as it developed, there was an incomplete knowledge of the changing status of the furnace. During abnormal plant conditions there should be a competent senior manager detailed to retain an 'overview' of the developing situation and to keep a specific watching brief on critical parameters, so as to be able to inform those more intimately involved in dealing with the abnormal situation. Specific parameters in the case of blast furnace recovery operations should include such critical data as liquid iron levels, hydrogen levels and trends.

Management of change

Lesson 11 A formal system of pre-modification risk assessments should be instituted for any changes (including changes to operating parameters) proposed to safety-related plant and equipment. This should be coupled with post-modification safety reviews. The management of change system should include evaluation and assessment not only by the engineering and operational functions, but also by appropriately experienced and competent safety professionals. Duties and responsibilities for this should be clearly identified. Changes to the physical characteristics of plant should be carefully assessed for any impact on risk profiles and should be carried out with best engineering practice. All such changes should be carefully recorded and subsequently re-evaluated to determine their actual operational impact.

Decision making

Lesson 12 In emergency situations, there should be management arrangements such that there is a clear 'line of responsibility' for decision making. There should be no doubt whatsoever as to who is making which decisions.

Lesson 13 Decisions made by managers under pressure from adverse plant or process conditions present a potential source of significant error. Adequate training and experience is essential, but more precise decision-making protocols should be available for foreseeable circumstances to guide and inform decision making. Careful consideration should be given to providing emergency event-simulation training etc to build operator confidence and skills in emergency or abnormal process conditions.

Design issues

Lesson 14 Opportunities to achieve risk reductions by radical design improvements on blast furnaces are very infrequent. The design of new or extensively rebuilt furnaces should take into account the need to improve the reliability of cooling water supplies and to have suitable pipework layout, valve arrangements and water monitoring systems so as to facilitate prompt leak detection and remedial action.

Lesson 15 The provision of improved monitoring systems, purpose-built for monitoring cooling water parameters on blast furnaces, should be considered. Safety-specific instrumentation of adequate precision should be designed and installed to address specific foreseeable operational and abnormal operating conditions.

Human factors

Lesson 16 It is essential during abnormal plant or process conditions that all personnel are clear as to who is responsible for decision making and that they have provided adequate lines of communication. Employees should have a precise and clear view of their roles and responsibilities, and be supported by suitable training, procedures and other job aids.

Lesson 17 The awareness of the danger of water/metal and water/slag explosions should be raised among all employees engaged in processes where this is a risk. The degree of risk presented by molten materials coming into contact with water continues to be not fully appreciated.

Lesson 18 The process risks associated with safety-critical plant, especially ageing plant, should be thoroughly understood through rigorous assessment processes, with these being subject to regular review. Specifically, with water systems on blast furnaces, a ‘leakage tolerant’ attitude should not be allowed – especially with older furnaces. Such raised acceptance of water leaks increases the risks of an adverse event occurring at some point.

Background

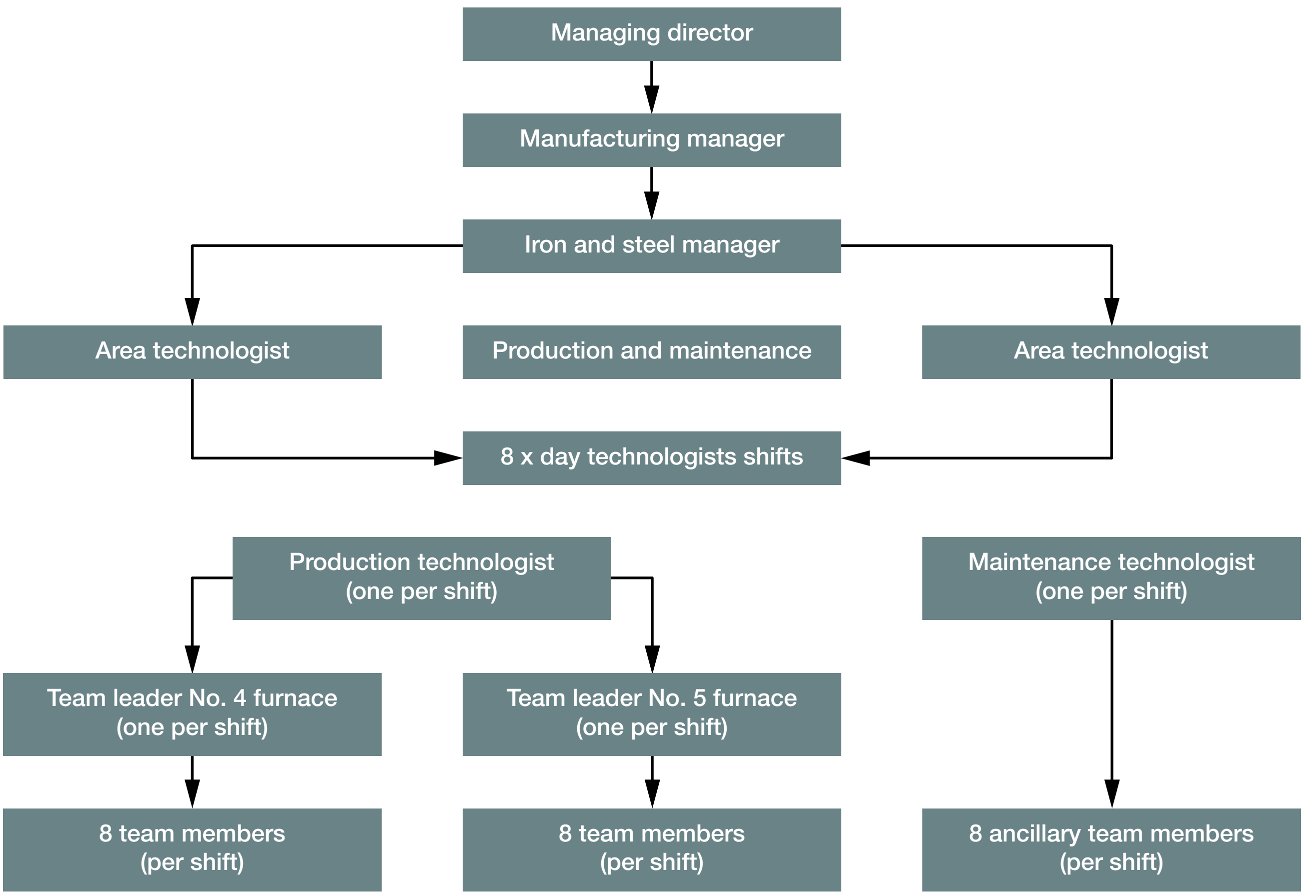
The company

15 The company was formerly known as British Steel Plc. It was, at the time of the accident, Corus UK Ltd, this company having been formed in 1999 following a merger between British Steel Plc and the Dutch steel maker, Hoogovens. Steel making has been carried out on the site for many decades, both in public and private ownership; generations of local residents have been employed at the premises. Employee numbers at the time of the incident were circa 3500; the company also employs considerable numbers of contractors.

The plant

16 Port Talbot is an integrated steelworks manufacturing flat steel products for a very extensive range of industries. Iron is made on site from basic raw materials in two blast furnaces (designated No. 4 and No. 5 for historical reasons); this is then converted into steel. The two furnaces at Port Talbot at the time of the explosion were fundamentally different: No. 5 was to a 1950s design, albeit much modified over the years; No. 4 was constructed in the early 1990s to a much more recent Japanese design.

The management structure



The blast furnace

The structure of the blast furnace

17 No. 5 Blast Furnace at Port Talbot was a conventional ‘column–supported’ furnace of a type in use worldwide. It consists of a large (circa 90 m) vessel supported on heavy steel columns. The charging and discharging arrangements, together with systems for dealing with the gases produced in the process, are shown in Figure 1.

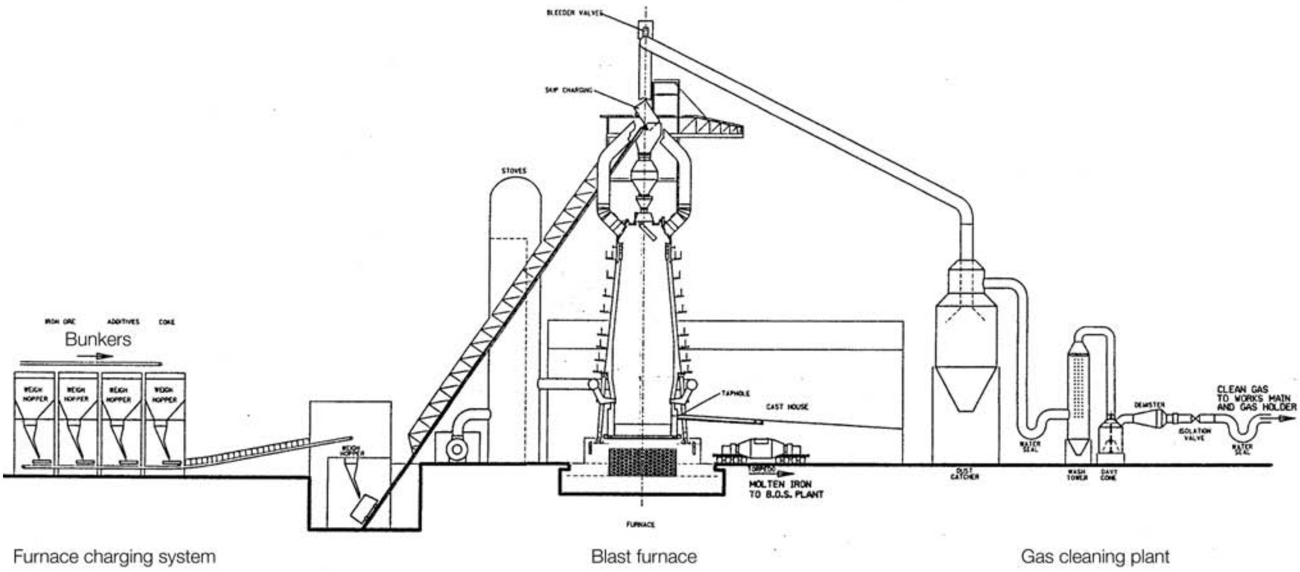


Figure 1 Diagrammatic arrangement of No. 5 Blast Furnace and ancillary plant

18 To understand the significant features referred to in this report, Figure 2 may help.

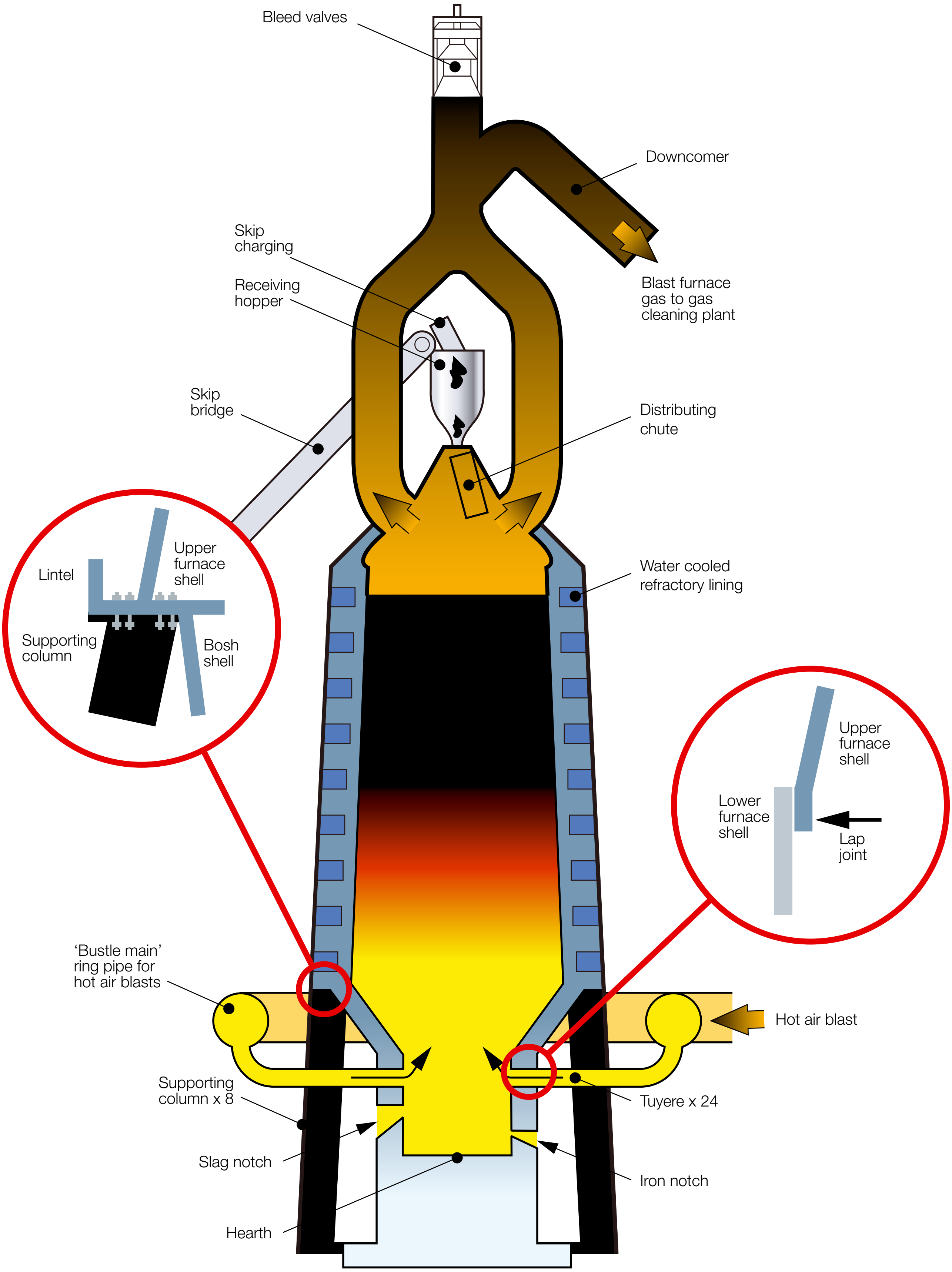


Figure 2 Blast furnace showing significant features

The iron-making process

19 The purpose of a blast furnace is to produce iron by chemical reactions on iron oxides (iron ores) and convert them into liquid iron. This is achieved by 'charging' iron ore, coke, sinter (a product of iron ore fines and coke), and limestone into the top of the furnace and subjecting these materials to a series of complex chemical reactions within the furnace. The charge materials (or 'burden') gradually works its way down the furnace vessel, reacting chemically and thermally as it does so. At any given time the furnace burden can amount to around 1800–2000 tonnes of materials. Preheated air or 'hot blast' is blown into the furnace via nozzles known as 'tuyères'. This blast air is an essential part of the process – typically it will be heated up to 1100 °C. The raw materials introduced into the top of the furnace take some six to eight hours to descend to the bottom of the furnace where their conversion into liquid iron and slag (ie molten waste material from the furnace) is completed. The liquid iron and slag is then drained or 'tapped off' at regular intervals from the furnace.

20 In addition to liquid iron and slag, large quantities of hot gases are produced in this process. The gases exit the furnace through 'uptakes' which merge into the 'downcomer', the large gas offtake running from the top of the furnace to the gas plant. On exiting the downcomer the gases are cleaned and cooled to allow them to be used for combustion purposes. Some of the cleaned gas is directed to 'stoves' where the gas is burned to produce further hot blast air for the furnace.

21 An essential feature of the iron-making process is that, due to the chemical reactions taking place, the whole process is intensely exothermic, ie it generates considerable heat. Therefore there is an essential requirement for cooling of the furnace shell and lining.

No. 5 Blast Furnace

22 No. 5 Blast Furnace was constructed on site by an American Company, Davy International, and was completed in 1959. It was known as a lintel or column-supported furnace. The lintel was a large structural steel ring supporting the furnace stack. A great many furnaces of this design were constructed from the 1940s onwards, and many furnaces of similar design are currently operational throughout the world. The furnace was in essence a two-part steel vessel, with the upper part – the stack – supported via the lintel on eight large steel columns, each attached to the lintel by eight large bolts. The lower part of the vessel comprised the 'hearth', a crucible holding molten metal and slag, and the 'bosh', an outward sloping section just above the hearth. The two-part steel vessel had what is known as a 'lap-joint' at the interface between the two sections. This was a sliding and overlapping joint to allow for the expansion of the shell and refractories. This overlap of the two parts of the steel shell plate was some 200 mm.

23 The shell was heavily lined internally with refractory material. The shell was also fitted with numerous cooling elements intended to allow a constant flow of circulating cooling water. Cooling elements were located within the refractory lining to convey away thermal energy and hence prolong the life of the lining. Although coolers were located throughout the shell there was a greater concentration in the lower areas where the greatest heat was generated.

24 Starting in the early 1970s, the original shell and cooling elements had been subject to extensive replacement and modification. This was to be expected as inevitably the refractories, and eventually the shell, will deteriorate with time. The replacement of the shell at this time allowed the fitting of coolers of high-purity

copper. At the time of the accident the majority of coolers in No. 5 Blast Furnace were constructed from this material, although there were also a lesser number of cast-iron coolers.

25 The purpose of the blast furnace refractory lining is to enable the furnace to resist the intense mechanical, chemical and thermal conditions within its interior. The precise composition of the refractory again depends on where within the furnace the lining is to be installed. Tougher, more abrasion-resistant materials tend to be located at the upper sections, where mechanical abrasion is prevalent, with more chemical-resistant materials used lower down in the furnace where the liquids that are formed are chemically active. It is a feature of blast furnace practice that the furnace lining will inevitably deteriorate during the operating period of the furnace. This gives rise to each such operating period being known as a 'campaign'.

26 The purpose of any blast furnace is to convert iron ore (containing many impurities) into liquid (pig) iron. The generic name given to the mix of materials charged to the furnace – specifically coke, limestone and iron ore – is the 'burden'. This is introduced ('charged') to the furnace via an inclined skip hoist which travels up a large inclined skip bridge. The burden is introduced into the furnace through a gas-tight distribution system at the furnace top. This system is also designed to prevent the escape of gas from within the furnace during charging. The charging and distribution system is known as a 'Paul Wurth top' (derived from the name of the manufacturers).

27 Gas produced in the process is conveyed from the furnace to an adjacent gas plant by means of a large inclined pipe known as a 'downcomer'. Hot air is supplied to the furnace from the stoves via the 'bustle main'. This is a large circular pipe that surrounds the lower portion of the furnace. The bustle main supplies hot air through 'tuyères'. There were 24 tuyère assemblies on No. 5 Blast Furnace. In practical terms, the tuyère assemblies are nozzle systems through which the hot blast air enters the furnace. The tuyères are connected to the bustle main and blow heated air into the furnace hearth jacket.

28 Gas pressure produced in the process is controlled by a large valve device known as a 'Davy cone'. Excess pressure can also be relieved by three bleeder valves situated on the furnace top. The bleeder valves on No. 5 Blast Furnace could be operated both automatically and manually.

29 On No. 5 Blast Furnace there were two water-cooled tap holes to allow molten metal and liquid slag to be removed. When tap holes are not in use a mechanical device known as a 'clay gun' is used to block the tap holes with a plug of impervious ceramic material. In No. 5 Blast Furnace only one tap hole was normally used at any one time.

30 The lower operational area of the furnace was a partially enclosed structure known as the 'cast house'. The cast house on No. 5 Blast Furnace also contained the control room or 'jump desk' where electronic monitoring devices and computer mimics were housed to enable the operation and furnace conditions to be monitored and recorded constantly.

31 The control room provided operators with a good view of the furnace tuyères and tap hole areas.

32 The cast house floor accommodated refractory-lined 'runners' to channel molten slag and iron away from the furnace, molten slag either to the slag pits or the granulator, or, in the case of the molten iron, to large rail-mounted ladles known as 'torpedoes'. The iron was normally collected in these torpedoes for transportation to the steel-making plant.

33 Access to the upper parts of the furnace and equipment on it, such as the cooling system components, was by means of nine circular steel access platforms which were situated at regular levels up the body of the furnace. These were connected by steel access stairways.

34 At the time of the explosion, No. 5 Blast Furnace had produced over 14 million tonnes of iron during the campaign since the 1989 rebuild.

The cooling water system

35 The process of iron production is extremely exothermic, generating temperatures of over 2000 °C within the furnace, and the provision and maintenance of adequate supplies of cooling water is essential. The normal requirement on No. 5 Blast Furnace cooling system was for circa 80–90 thousand litres of cooling water per minute.

36 A complex cooling water system was provided to accomplish this, and basically comprised two main systems: the distribution system actually on the furnace and that supplying water to the furnace distribution system.

37 There are two basic types of furnace cooling water systems used on blast furnaces: they are described as ‘open’ or ‘closed’ systems.

38 In an open system water is drawn from a supply source, pumped through individual cooling circuits, returned via open-topped troughs known as ‘launders’ and then, by gravity, to open collection ponds and cooling towers. In closed water systems the various individual supply systems are self-contained and pump and recirculate the same water over and over again. Crucially, this type of system is not open to atmosphere at any point on the furnace, unlike an open system.

39 There was an open system on No. 5 Blast Furnace. The system was largely as it was originally installed. This design of system is commonly used on furnaces of this age throughout the world.

40 There were in excess of 1400 cooling elements on No. 5 Blast Furnace.

41 The majority of the coolers in No. 5 Blast Furnace were ‘flat’ or ‘plate’ coolers. At various locations within the furnace other specialised coolers, again usually copper but on occasion cast iron, were fitted to the furnace. These included:

- tuyère coolers – these were copper cooling elements at the end of the tuyères;
- stave coolers – these were large coolers made of cast iron;
- ‘big coolers’ – these were copper cooling elements fitted around the tuyère cooler and fixed into the hearth jacket; and
- tap hole staves – cast-iron cooling elements around the tap holes where molten metal and slag is drawn off.

42 There was also a large number of tubular copper cooling elements in the furnace. These are known as ‘Sorrelors’ (or on occasions, because of their shape, ‘cigar coolers’). There are operational benefits in the use of Sorrelor coolers in that they can be fitted relatively easily (by drilling a hole), and at any time, into areas requiring additional cooling, unlike flat coolers which generally require far more work to facilitate installation or replacement. A number of Sorrelor coolers had been fitted to No. 5 Blast Furnace during its campaign lifetime, especially since the mid-1990s.

43 The continued efficiency and integrity of coolers is entirely dependent upon a constant flow of cool water through their internal channels and labyrinths. If the supply of water to a cooler is interrupted, any residual water within the coolers will boil and evaporate. This in turn can rapidly cause the cooler to melt or 'burn out'; copper has a melting point of circa 1083 °C, much less than the temperatures encountered in parts of the furnace. Coolers can also fail through other mechanisms such as, for instance, mechanical abrasion.

44 The speed and extent to which coolers will burn out depend on a number of factors: their position within the furnace (coolers in the bosh and lower stack areas are particularly vulnerable); how long the supply is interrupted; the existing condition of the cooler; and whether the cooler has any protection by 'scabbing' (accretions of solidified silicaceous material adhering to the cooler body). As originally fitted, coolers will be covered, and protected, by refractory material. As the refractory material erodes back towards the shell as the campaign progresses, the coolers progressively lose this protection. While this is entirely normal, it does give rise to increasing cooler vulnerability to mechanical and heat damage. The gas pressure within an operating furnace is less than the water delivery pressures within the coolers. Once a cooler has failed, water from the pressurised system will flow directly into the interior of the furnace, potentially disrupting smooth furnace operation and eventually leading to risks to safe operation, depending on the amount of water entering the furnace. Importantly, if the water supply to a failed cooler is subsequently restored, the potential for a serious water leak into the furnace is considerable.

45 Once a failed cooler has been identified it is generally either removed and replaced or 'grouted up' with aluminium oxide grout.

The cooling water supply system

46 The cooling water supply system for No. 5 Blast Furnace, at the time of the accident, was from a facility known as Margam B Power Plant and comprised:

- two 'Sulzer' pumps – large electrically driven water delivery pumps deriving their name from the manufacturer;
- two steam turbine-driven delivery pumps (referred to as 'turbo pumps' 'T1' and 'T2');
- three electrically driven cooling water pumps (associated with the evaporative cooling towers); and
- one cooling water tower together with associated fans.

47 Also provided was an emergency water make-up system. This was a tower-mounted tank, designed to operate if the delivery water pressure dropped below circa 3.7 bar, and release water from the tower into the furnace main. This system operated at a lower pressure than the normal furnace water supply pressure and it was primarily designed to provide cooling water to the lower part of the furnace while emergency shutdown procedures were followed.

48 Water drawn from the cooling tower cold-water sump was intended to be pumped continuously to the furnace using two individual main supplies and at an agreed control standard of flow and pressure. A proportion of the returned water was passed over the cooling tower, some was filtered; a small amount was added to make up any losses.

49 The two electric Sulzer pumps were each capable of supplying water at 45 000 litres per minute. The turbo pumps, T1 and T2, had a capacity of 45 000 litres and 34 000 litres per minute respectively. Normally two 45 000 litres-per-minute units would be run simultaneously to supply sufficient cooling water to the furnace.

50 The normal practice at No. 5 Blast Furnace was to run one electric Sulzer pump and steam-driven turbo pump T1, each delivering 45 000 litres per minute.

51 Normally, the second Sulzer pump would be on automatic standby. Any loss of pressure would be detected by pressure switches set to automatically call for the standby unit to start should water pressure fall below a predetermined level.

52 There was instrumentation at the plant which allowed the monitoring of the total flow of water and water pressure and individual header flows and pressures. Temperatures were also monitored at several points including the launders, hot well and main manifold. Crucially, there was no instrumentation (such as flow meters) provided on the system to measure the quantity of any water loss from the system into the furnace.

53 The water supply, pumps and associated equipment were controlled, maintained and managed by the work's Energy Department, which provided this function for both furnaces.

The event

The explosion

54 The explosion occurred at approximately 17.13 hours on 8 November 2001. There was little or no warning to personnel working on the cast house floor, although some witnesses later spoke of the event being preceded by 'rumbles' within the furnace moments before the actual explosion. At the time of the explosion there were three employees actually on the furnace stack, and several employees and contractors in the cast house floor area. Three employees were within a few metres of the tap hole, with several in the 'jump desk' (control room).

55 The accident event began with a rapid over-pressurisation of the furnace contents in the bosh area due to the interaction of water and hot molten materials. The immediate effect of this furnace over-pressure was to lift that part of the structure above the lap joint upwards, the furnace lintel rising up off the column heads normally supporting the furnace. It is estimated that the structure above the lap joint rose by some 0.75 m. This structure, with its associated burden, was estimated to weigh around 5000 tonnes. The lifting of the upper part of the furnace left an opening of approximately 400–600 mm around the entire circumference at lap joint level. Gases and hot materials were ejected horizontally from this opening. During the period that this gap remained open, some 200 tonnes of liquid, solid, and semi-solid material were ejected onto the cast house floor. Gaseous material and dust rose into the cast house, exited through various openings in the building and into the atmosphere, where much of it ignited. A cloud of ignited dust and gaseous material was thrown several hundred feet into the air above the furnace. The furnace-top 'bleeder' valves also opened and discharged into the atmosphere. Gases from these valves also ignited.

56 The furnace then fell back down vertically as the pressure decreased. During the explosion it had twisted (anticlockwise) through approximately 20–50 mm and moved a distance off-centre of about 100 mm, leaving it supported on the lower lap joint plate, with the lintel mounting positions no longer in contact with the column top flanges but instead some 50–100 mm above the column tops. This meant that the weight of the furnace stack was resting, eccentrically, on the lower lap-joint plate.

57 During the movement of the furnace, many of the various water supply pipes to the furnace were ruptured; for some time, the water supply continued to flow from these pipes into the cast house and onto the hot materials which had been discharged, flooding the cast house with very hot water and steam. The gas offtake system was severely jolted, but furnace gas containment at the gas plant and top of the furnace vessel was maintained throughout. The whole event lasted only a few seconds.

The casualties

58 There were three deaths. One employee died at the scene, another in hospital shortly after. The body of a missing third employee was recovered from the slag pit area the following day. A dozen or more employees and contractors were admitted to hospital, with some of these remaining in intensive care for several months. Their injuries included burns of varying severity and other injuries including serious fractures and lung damage from the inhalation of hot gases and dust. Several individuals had very serious burns and multiple injuries of a life-threatening nature. The injuries arose from blast effects, burns from the hot gases and dust ejected, and burns from hot water and steam. A number of personnel present were subsequently also diagnosed with post-traumatic stress disorder.

The damage

59 Damage was generally limited to the confines of the blast furnace area.

60 The lifting of the furnace body caused considerable disruption to all its services and associated plant. The furnace structure immediately after the accident was no longer supported directly upon its structural columns and was therefore in a potentially unstable condition.

61 Hot materials comprising molten slag, molten iron, partially reacted coke, sinter and unreacted coke, together with larger lumps of agglomerated burden material, had been ejected through the open lap joint that also damaged the blast wall immediately behind the west side of the furnace. Subsequently, furnace burden penetrated into the water manifold/launder area and into the hydraulic room destroying the water manifold and damaging the wall of the hydraulic room beyond. Penetration of molten burden through a doorway into the amenities block initiated a significant fire which caused serious damage.

62 The profiled steel cladding of the building was severely damaged in several areas, with some sheets being projected in excess of 40 m. Molten slag was thrown over most of the cast house floor and flowed as far as the entrance ramp to an estimated depth of between 300 and 600 mm. There was no penetration of solid material into the control room, although there was impact damage to its front. The lights in the cast house roof were undamaged.

63 Areas where gas plant structures had moved significantly were identified after the accident, but gas containment was maintained and there was no major blast furnace gas leakage from the downstream gas system. Significant amounts of flame and gas were, however, emitted through the furnace top bleeders.

64 Subsequent engineering evaluation by Corus engineering personnel deemed the furnace to be beyond repair; the decision was taken to demolish and rebuild, and this work was put in hand within weeks of the accident.

The mitigation

65 Following the explosion, the existing site major emergency plan was immediately triggered. After the explosion, the remaining furnace contents were still 'active', and generating large quantities of blast furnace gas comprising mainly carbon monoxide.

66 Within a short time of the event, blast furnace personnel had established a large water seal at the gas system to isolate the furnace from the downstream gas systems. The water supply from the Energy Department was isolated. The furnace was vented through its flare stack and bleeder valves.

67 The structural stability of the furnace and its associated plant was a matter of immediate concern. Following engineering inspection, remedial works were put in hand to ensure stability and safety.

68 The furnace was largely sealed in preparation for 'quenching'. This involved the carefully controlled addition of thousands of tonnes of water to the furnace contents over a period of weeks to halt the internal reactions, stop gas generation, and put the furnace into a safe condition for demolition. Once necessary forensic examinations had been completed, the 'quenched' burden and the refractory materials within the furnace body were removed. The furnace shell was cut into sections and dismantled. The lower bosh and hearth material was essentially solidified and was not finally removed until most of the furnace structure had been dismantled.

The investigation

69 The Work-Related Death Protocol was triggered soon after the accident was reported. The South Wales Police Major Crime Support Unit assumed primacy for the joint investigation with HSE; after some eight months primacy passed to HSE. Significant police forensic science input was also committed, as was specialist support from HSE's Field Operations Division, together with major technical input from HSL.

70 As the investigation developed, expert opinion was sought from Canada, Germany and the United States. A Major Investigation Management Board was appointed to oversee HSE's activities.

71 The Crown Prosecution Service was involved throughout the investigation, in particular with the legal issues surrounding the consideration of potential charges of manslaughter against any party. There was a Corus investigation of this accident in accordance with the company's well-established accident inquiry procedure as agreed with the trades unions.

The history of No. 5 Blast Furnace and the campaign extension

72 The construction of No. 5 Blast Furnace was completed in 1959. Following three relines, in 1972 the furnace underwent a major rebuild. In 1979 the mid-stack section was replaced and additional coolers added.

73 In 1989 a further furnace reline took place. The refractory lining was replaced and upgraded. Additional coolers were installed which led in turn to increased water supply requirements. On the 22 March 1989 the Planning Committee of British Steel Plc recorded that a rebuild of No. 5 Blast Furnace was planned for 1995/96.

74 In 1992 an incident during the repair of the stove brickwork at No. 5 Blast Furnace depressurised the furnace and necessitated a furnace 'recovery' over a number of days.

75 In 1994 there was a 'breakout' of molten metal from the furnace, caused – it is believed – by water leaking from tuyère coolers. Substantial damage to bosh coolers resulted, but no injuries. During the course of the recovery of the furnace following this incident, a run of slag had occurred from the lap joint, and the decision was taken to 'box in' the lap joint. This, in some measure, adversely affected the ability of personnel to quickly detect water leaks. Sorrelor coolers were installed in the tuyère breast area at this time.

76 Following the 1994 episode, a decision was taken to extend the campaign life of No. 5 Blast Furnace and an 'Extension Committee' formed. On 5 September 1995, at a meeting of the 'No. 5 Steering Group Committee', a 'Campaign Extension' team was formed with the objective of extending the campaign to at least 2000.

77 At a meeting of the No. 5 Steering Group Committee on 9 April 1998, an intention to extend the campaign life to 2003 was noted. That was reiterated at a meeting of the Steering Group Committee on the 8 July 1998.

78 This committee was chaired by a senior blast furnace manager, and comprised experienced representatives from Engineering, Production, and Energy Department staff. No Safety Department staff or others with professional risk assessment expertise attended any of the many meetings of this committee.

79 The 'Extension Committee' (as it became known) met four times a year from 14 December 1994 to 18 October 2001. It had a budget of £1 million per year.

80 The overall result of the Campaign Extension Committee's deliberations and actions was that the proposed furnace rebuild originally planned for 1996 was, subject to a rolling two-year review, extended to an indeterminate date into the future. The Committee continued to meet on a quarterly basis.

Forensic examination of No. 5 Blast Furnace

81 No. 5 Blast Furnace at Port Talbot is shown diagrammatically in Figure 2 and Appendix 5.

82 Detailed forensic examination of the furnace following the explosion revealed the following:

- the furnace stack was resting on the lap joint rim;
- the lintel beam was no longer in contact with the eight supporting column heads;
- the securing bolts for column heads to lintel were all broken (except in the case of one column head (column 3) where the entire head plate had fractured, complete with bolts);
- the securing bolts (and weld at column 3) had been fractured a substantial period of time before the incident;
- the furnace shell showed significant distortion due to heat in the lower stack area above the tap hole;
- a number of coolers were found to have been leaking badly (see Appendix 2 for details of how many and which coolers);
- the refractory lining was well-worn but expert opinion deemed it to be in an acceptable condition for a furnace of this age; and
- a large mass of solidified iron, coke and sinter was found in the base of the furnace.

The Energy Department

83 Prior events at the Energy Department, and specifically Margam B Station, had a profound effect as precursors to the accident. The events described below were determined from departmental records, interviews and interrogation of recorded electronic data.

84 Between 30 September and 5 November 2001 there had been a substantial number of problems with the No. 5 Blast Furnace water pumps. During this period, for example, there had been six pump breakdowns and six serious faults reported. Pumps had failed on auto start on a number of occasions – among a range of other defects recorded. The situation was that during this period the overall pumping system had shown a significant lack of reliability.

85 For some time prior to the incident, routinely, the water supply to the No. 5 furnace had been provided by the two electric Sulzer pumps. Steam turbo pump T1 had been out of commission since early October 2001 awaiting the return of a refurbished gearbox. T1 was, significantly, still not available for use in the days leading up to the accident.

86 The provision of full furnace cooling water delivery relied upon the two electric Sulzer pumps. The standby pump was steam turbo pump T2, having the smaller capacity of the two turbo pumps at approximately 34 000 litres per minute.

87 In 1996 the motor for the Sulzer 1 pump was replaced. Because the manufacturers were unable to supply a motor to the specification required, the motor that was available was de-rated. The consequence of this was that it became necessary to operate the motor at circa 98–99% full load current (FLC), not 90% as originally planned.

88 The Sulzer motors were of the induction type. Induction motors are designed to maintain a constant power output. If the voltage falls, the motor draws more current to maintain, in this case, the required pump water pressure and flow. Consequently, if the supply voltage falls, the current increases.

89 When the new motor was installed the thermal overload protector was not altered or adjusted to reflect operation of the motor at 98–99% FLC rather than the original specification. Instead it was set to operate at 110% FLC.

90 The failure to adjust the thermal overload protector reduced the margin of spare capacity from 22.2% to 11.7% – a 47.3% reduction, which was highly significant and crucial.

91 In simple terms the thermal overload protector on Sulzer 1 had not been adjusted to accommodate the higher kilowatt rating of the new motor when fitted. This meant that, on 7 November, it tripped too soon.

92 On the 7 November 2001, a simple maintenance task was scheduled, by the Energy Department, to repair electrical equipment associated with the electrically-driven Sulzer pumps.

93 The No. 5 Blast Furnace crew had not been informed of the intention to carry out this work. Communication between the Energy Department and the blast furnace crew had been identified by the company as a problem on previous occasions.

94 The work was found to be necessary due to steam ingress to a transformer control cabinet. To facilitate the repair, electrical feeds were switched and in the process there was a voltage drop of 6.7%, which caused number 1 Sulzer pump to trip out as the current increased.

95 The rise in current was a direct consequence of the reduction in supply voltage. The Sulzer was running at 98–99% of its FLC, too close to its tripping current of 110%; it was highly vulnerable to input voltage shortfalls.

96 There were no written procedures for ensuring that those responsible for switching transformers checked the voltage output, although this was known to be an essential task.

97 At this time, around 09.16, the smaller of the two turbo pumps (T2) automatically came on to compensate when number 1 Sulzer pump tripped out. This pump (T2) also tripped out (on its over-speed protection) within seconds, probably because a steam governor setting was too high, allowing the ultimate (safety) trip speed to be reached quickly (due to speed 'surge') after start up. The ultimate trip speed device operated, 'de-latching' the pump from its steam supply valve, and shutting down the pump. (The important fact here is that T2 standby failed to come online as it was required to do.)

98 As a consequence the furnace was, for a period of some 10–12 minutes, receiving only approximately 55% of the required cooling water supply.

99 The emergency water tower did not come online as the reduction in water pressure was insufficient to cause this to operate.

100 At around 09.25 the electrical supply to number 1 Sulzer pump was restored. On noticing the initial reduction in the flow of cooling water, the furnace crew, in accordance with established procedures, had 'dropped the wind' to reduce the flow of hot air from the tuyères. With the water flow to the furnace restored, the furnace was gradually put back 'on wind'. A search for leaking coolers was initiated when elevated hydrogen readings were later detected, indicating a water leak into the furnace. The immediate assumption, subsequently proved to have been correct, was that coolers had burnt out because of the reduction in cooling water supply.

Leak detection

101 The detection of leaking coolers on the furnace was the duty of technicians among the furnace crew known as 'watermen'. In any furnace design, but especially one with open-circuit cooling arrangements, the job of detecting leaks was known to be difficult.

102 There were a number of additional factors with No. 5 Blast Furnace which made the task of detecting water leaks even more difficult. They included:

- the multiplicity of pipework, described by some as being 'like spaghetti'. This was caused as a consequence of installation of Sorrelor coolers to provide additional cooling at places where the refractory lining had become thin and at other hot spots;
- open launders into which water from the coolers was discharged had been covered to keep out debris. This hindered and obscured visibility and accessibility in checking for leaks;
- some water discharge pipes were slipping into the launders and were preventing visibility of outlets;
- some water discharge pipes had additional flexible hoses attached which ended up at the base of the launders and totally submerged;
- water outlets were on different landings from the coolers;
- there were valves provided which, when turned off, would shut off large numbers of coolers at a time. The ability to do this would have speeded up the detection of

water leaks. The valves were in poor condition, were not working on 7 November and could not, therefore, be used to isolate banks of coolers at a time. There had been a programme to have the valves repaired in the summer but this was not implemented for budgetary reasons.

103 It should also be understood that the watermen were doing much of their work on the furnace while wearing breathing apparatus, which made an already difficult task even more challenging.

104 Detection of water leaks at furnace No. 5 was, therefore, a difficult task in any event. For it to be done properly it required experienced watermen and an effective system, including labelling and tagging, to identify which coolers had been switched off, checked and switched on again. This was particularly important in the light of the multiplicity of pipework.

105 The day technologist, the most experienced waterman, was not at work on 7 or 8 November. The senior man overseeing and advising the watermen was very inexperienced.

The recovery

106 After the pump trips earlier in the morning, by 10.45 on 7 November, the furnace was back up to normal capacity. On bringing the furnace back on to normal operational wind rate, a rise in hydrogen levels in the analysis of the top gas had been noted, indicating the ingress of water into the furnace (the elevated hydrogen readings being due to dissociation of water into its component oxygen and hydrogen molecules inside the furnace). The monitoring screen alarms at 10.11 indicated that the increased percentage of hydrogen was significant (this would normally run at below 2%). Despite attempts by the watermen no leaks could be found. Sometime after 11.30 a decision was made to take the furnace off wind. Subsequently the furnace shutdown was postponed until 14.30 because some molten iron and slag was still being run off the furnace.

107 At approximately 13.00, charging of the furnace had ceased.

108 At about 13.00 an area technologist saw a ‘greeny–yellow’ flame coming from the (boxed-in) lap joint area, around tuyère No. 3, that he believed to be a hydrogen flame and indicative of water ingress. All the tuyères were checked and found to be satisfactory except for numbers 3 and 4, which were described as ‘wet’. Water could be seen dripping within the furnace (through the ‘peep-sights’ of the tuyères). The water system was then rechecked later in the afternoon by experienced contractors, who discovered that a bank of Sorrelor coolers had not been tested.

109 After 19.00 ‘backdrafting’ was undertaken as a prelude to bringing the furnace back on. This is a process whereby there is a reversal of the blast air flow to stoves to ease the pressure within the furnace.

110 At approximately 19.00 three failed Sorrelor coolers on the third landing were identified, bypassed and grouted, effectively isolating them and what was thought to be the source of the leak. These coolers had been leaking since the water starvation that morning, some 10 hours previously. (Subsequent forensic tests indicate that many tonnes of water may have entered the furnace during this period.) At 23.30 the furnace was brought back on wind (at low pressure – 0.35 bar) and charging recommenced.

111 At just after midnight on Thursday 8 November a first attempt was made to achieve a ‘connection’ with molten iron by drilling the tap hole. This and a subsequent attempt were unsuccessful and on the second occasion there was a

blow out of 'orangey' coloured flame from the tap hole – indicating the presence of hydrogen. This was taken as an indication of a poor connection with molten iron.

112 'Lancing' at the tap hole then commenced. Lancing is the manual use of thermic lances (essentially a long, consumable, steel tube fed with pressurised oxygen gas) to burn into solidified material within the furnace to establish a 'connection' with molten liquids, either iron or slag. Lancing is carried out in recovery conditions because it can reach higher areas of the hearth where liquid iron is actually being formed. At 00.30 the first attempt was made to cast (ie run off molten material). Gas flames and some slag were released from the south tap hole but there was no flow of iron.

113 Initially the decision was made to lance 'horizontally' at the tap hole. At 01.30, in view of the limited success of horizontal lancing, a decision was made to lance 'up', ie lance at an upward angle into the furnace to try to reach molten iron.

114 Lancing continued through the night at an upward angle to the hearth.

115 At 02.00 slag was noted to be entering tuyère No. 20. At 02.30 there was contact with iron and a slow flow obtained. At 03.35 there was what was described as a small run of iron.

116 At 04.45 an area technologist was telephoned at home and advised that difficulty was still being experienced in withdrawing material from the furnace. He arrived on site at approximately 05.30.

117 At 05.15 a decision was taken to use larger 1 inch (25 mm) diameter lances as opposed to the ¾ inch (20 mm) lances then in use. These delivered considerably more oxygen to the tip of the lance, and thus much greater heat.

118 At around 06.00–06.30 there was a shift changeover.

119 At approximately 07.00 it was noted that tuyères 6 and 7 were blocked, that Nos. 16 to 20 were bright and working well, Nos.14 and 15 were reasonably good, but that the others were described as 'closing'.

120 At 08.00 there was a small run of iron, and between 08.00 and 09.00 there was another run of what was described as 'poor quality' iron.

121 At around 10.00–10.30 a progress meeting was held. The consensus of the meeting was that progress was being made and the work would continue to try to run off iron and slag throughout the day. A further review meeting was set for 16.00 that afternoon.

Second water ingress (on 8 November 2001)

122 At 12.50 on 8 November, monitored hydrogen levels increased to more than 7%, indicating significant further water ingress to the furnace. At 13.00 hydrogen levels were seen to be still rising, again indicating further water ingress. The furnace remained on wind while watermen on the furnace stack tried to locate the leak.

123 At 15.30 lancing recommenced. Only six tuyères were now noted to be still operating; the remaining 18 tuyères were blocked.

124 At 16.00 the pre-arranged team meeting took place. A number of senior and experienced staff were present at this meeting. Concern was expressed that there might be a risk of an uncontrolled 'breakout' of hot metal from the tuyère area. A 'tuyère breakout' is where the molten iron or slag penetrates through a failed

tuyère. A 'breakout' can also happen when molten iron penetrates through the refractory and steel shell of the furnace and flows in an uncontrolled manner from within the vessel. Any breakout represents a very hazardous situation with serious risk to personnel. This risk of breakout was clearly identified as the primary safety concern at that point by the staff involved at the meeting.

125 At the 16.00 meeting a decision was taken to continue with the recovery process until the following morning, when the situation would be reviewed again at 07.00.

126 At approximately 17.12 an employee working close to the tap hole saw something at the lap joint which he believed was possibly an indication of an imminent breakout of slag. He shouted 'run'. Almost immediately thereafter, the explosion and rupture of the furnace occurred.

Conclusions

Proximate causation

127 No. 5 Blast Furnace exploded due to significant internal over-pressure brought about by the interaction of water and molten hot materials within the lower part of the furnace.

128 The over-pressure primarily vented itself through the lap joint above the tuyères area, the furnace lifting off its supporting column heads.

129 This event was brought about by:

- a failure of two of the three available 'safety-critical' cooling water pumps, at approximately 09.13 and 09.15, respectively on 7 November 2001;
- the operation of the furnace on blast for 10–12 minutes with only 55% of its water cooling needs, leading to the overheating of some furnace coolers (circa 09.15–09.26, 7 November 2001);
- the consequential failure of perhaps three Sorrelor-type coolers, leading to serious water leaks into the furnace (beginning at about 10.00 on 7 November);
- a prolonged delay in the furnace watermen detecting and dealing with the source of this water ingress; as much as 50–80 tonnes of water entered the furnace by the time the source of the leakage was located and sealed at about 18.30–19.00 on 7 November;
- the furnace was put into a 'chilled hearth', and thereby a 'recovery' situation by these events, ie the large amount of water in the lower areas of the furnace had the effect of significantly lowering thermal activity;
- in the process of attempting to recover the furnace, and following additional leaks on 8 November 2001, a quantity of water came into intimate contact with, and reacted with, hot molten metal and/or hot molten slag, resulting in a massive release of energy leading to an over-pressure of the furnace interior;
- the furnace lifted some 0.75 m off its column heads. The large bolts between the furnace supporting columns and its circumferential lintel had been fractured some significant amount of time before the explosion and offered no impediment to this motion.

Precursor causative matters

130 There were significant precursor events going back many months, indeed years. Many relate to the operation of the Energy Department and the furnace Extension Committee. The British Steel Audit Reports (1994 and 1999) had identified a number of these precursors in advance of their manifestation.

131 Some notable precursors were:

- the failures of the pumping system on 7 November were part of a continuing and deteriorating pattern of failures. There were a series of serious pumping problems in the weeks before 7 November;
- the two pumps (Sulzer 1 and Turbo T2) that failed on 7 November were set to operate unduly close to their tripping criteria. The safety margins were thereby reduced significantly. Moreover, the latent shortcomings of Turbo T2 (governor and trip device faults) were not detected and remedied prior to 7 November 2001;
- these technical problems were matched by procedural weaknesses in the Energy Department. Of particular importance was the total lack of written procedures for reliability-sensitive maintenance work;
- training and supervision of key energy personnel were inadequate;
- the communication arrangements within the Energy Department, and between the Energy Department and furnace staff, were not sufficiently robust;
- the Port Talbot Energy Department was recommended in 1994/95 to carry out assessments of the durability of the No. 5 water cooling systems with a view to securing their reliability to the end of the extended life of the furnace. This important work was not carried out;
- insufficient steps were taken to ensure the long-term safety of the systems. The water cooling system as a whole was not seen as safety critical. This was a fundamental contributory factor;
- no safety professional, reliability, or risk assessment experts were members of the furnace Extension Committee, nor were any involved in its work;
- there had been no effective maintenance of the column head/lintel bolts. Had these been intact, it is possible that the lap joint may not have opened (although there is the possibility of the furnace rupturing elsewhere had the over-pressure been sufficient).

Lessons and recommendations

Safety management

Lesson 1 The company should review the role and function of the Safety Department. It should be better integrated into operational and engineering management.

132 This was a criticism levelled at British Steel as far back as 1975 following the Appleby-Frodingham furnace accident in which 11 men died. The investigation of the No. 5 Blast Furnace event of 8 November 2001 revealed little involvement of the Safety Department in, for example, process risk evaluation, during the critical campaign extension debates. The Safety Departments within the company are professional, competent, and relatively well resourced. However, integrated use of this competency in dealing with changes in risk profile etc was found to be patchy. Production management did not regard the professional safety advisers as having a significant role to play in change management. This has been addressed through a review of the functions of the Safety Departments and an examination of how the Engineering and Production Departments manage change.

133 It is recognised that with the impact of the Control of Major Accident Hazards Regulations 1999 (COMAH) and the regimes that they bring with them, that the company's approach to process safety has inevitably changed in many respects. However, it is essential that the Safety Departments are fully consulted in respect of significant process changes, even where the full weight of COMAH Regulation compliance is not involved. Had there been greater and more direct involvement of the professional resource that the company already possessed in the field of safety, the likelihood of an event such as occurred on 8 November 2001 could have been significantly reduced.

Lesson 2 Blast furnaces are now under the COMAH regime, where identification and evaluation of major hazards is a legal requirement. Before this, predictive tools and techniques have had relatively limited use within the steel industry. Predictive tools for the assessment and management of risk should receive greater use within the steel industry and other process industries: eg Hazard and Operability Studies (HAZOPS), Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Process Hazard Review (PHR), and Layers of Protection Analysis (LoPA).

134 There was little evidence that any of the well-established predictive tools used in other high-hazard industries had widespread use at the time within the company – or indeed the steel industry generally. (Fault Tree Analysis had, however, formed part of the company's preparation during 2000 for their COMAH submissions). This is changing with the changes in legislation (eg COMAH), but there is a role in a wider sense. Levels of predictive techniques competency outside the Safety Departments were low; use of the techniques were equally low. Use of these techniques might well have identified and eliminated some of the earlier precursor events leading to the furnace explosion.

Cooling water

Lesson 3 Sufficient cooling water for furnaces should be available at all times; the supply systems should have an adequate level of reliability built into the system. This reliability should be brought about by good engineering design (including an adequate level of redundancy) and suitable maintenance, and should be monitored to indicate any threats to its integrity.

135 The levels of reliability of the water delivery systems had not been properly evaluated on the basis of risk identification. Such reliability as existed had been brought about by 'custom and practice' design, largely based upon continued production requirements, not by any rigorous attention to risk evaluation. A more critical approach would certainly have identified potential and actual threats to system reliability.

Lesson 4 Reliability engineering techniques should be employed to identify safety-critical plant and appropriate safeguards should be developed from these studies.

136 Safety-critical plant had not formally been identified as such. Identification of plant whose function was essential had largely been on the basis of threats to production losses and identification of maintenance scheduling issues. The various 'critical' plant items and systems were not so identified on safety grounds although there was evidence post-accident that individual managers and technicians on site had recognised certain safety-related issues associated with critical process plant before the event.

Lesson 5 Closed systems for furnace cooling water, or systems with equal or better reliability, should be provided wherever reasonably practicable.

137 Closed system cooling arrangements offer considerable advantages over 'open' systems for rapid leak detection and are much more amenable to the fitting of diagnostic tools such as flow meters, make-up water determination etc. They are more reliable in terms of keeping the cooling circuits free from contaminants etc and are therefore an aid to better cooler maintenance, reducing scaling and fouling of the circuits.

138 The use of open-system cooling is historical, and lent itself to fairly accurate leak identification, monitoring etc, assuming the existence of long-serving, experienced watermen. Even with this proviso, however, all the evidence is that open systems are fundamentally much more vulnerable to fouling, corrosion and associated problems. With the advent of more modern technology for monitoring, and the possible lack of very experienced operators, closed systems will almost certainly prove far superior and reliable if properly designed, installed and maintained.

Leak detection

Lesson 6 Speed in locating furnace cooling water leaks is essential. Rapid leak detection relies on good engineering, adequate detection protocols, and suitably trained and competent operators. All operators of water-cooled furnaces should ensure that there are adequate measures in place to facilitate prompt leak detection.

139 The extent to which the delay in locating the various leaks into the furnace was crucial to the eventual extent of the furnace 'chill' and the final event of free water interacting with molten materials was substantial. Earlier leak detection on 7 November would have greatly reduced the risk of a severe furnace chill developing. There were significant predisposing features to the delay in finding the water leaks. Questionable training, experience and competencies, poor layout of pipework, inadequate cooler identification, and lack of easily implemented, systematic leak detection procedures all caused significant delays in dealing with a rapidly worsening situation. The fact that watermen working above tuyère level have to wear breathing apparatus to deal with the risk of carbon monoxide poisoning was also a significant addition to the physical difficulties involved in leak detection.

140 The provision of all reasonably practicable instrumentation and monitoring equipment, plus high levels of training and competencies among the operators should be paramount if water leakage is to be quickly identified and stopped. There should be clear leak-detection protocols for the actual process of leak detection, such that it can be carried out in an efficient and effective manner.

Lesson 7 On water-cooled metallurgical furnaces, where it is reasonably practicable, appropriate instrumentation, specifically designed for leak identification, should be installed to give earlier and more precise detection of leaking cooler elements.

141 There is little evidence that sufficient thought had been given to additional safety-related instrumentation for cooling water monitoring since the original build of the furnace. Although such instrumentation might have been of only limited accuracy, it may have been sufficient to attain some substantial risk reduction.

Retrofitting modern diagnostic technology had not been sufficiently considered; instead, reliance had been placed upon experienced and competent individual employees – employees who at the crucial time were, in some cases, not available.

Maintenance

Lesson 8 Maintenance, inspection and, where appropriate, testing of plant and equipment associated with the reliable delivery of water to furnaces should be paramount. The potential effects of lack of maintenance, inspection and testing in terms of safety should be clearly understood. There should be adequate prior communication between works departments when any maintenance or other work that may potentially affect safe plant operation or reliability is proposed. Formal protocols should be considered for this. Safety-critical items should be identified and protocols and priorities established for their maintenance, inspection and testing.

142 Safety-critical hardware components had not been identified as such. Had they been, other actions presumably would have been taken, eg in respect of the T1 turbo pump gearbox.

143 There was an important crisis precipitated due to the misunderstanding in respect of the planned work on the electrical equipment that led to the tripping of the Sulzer 1 pump. Whatever happened (there is conflict in the evidence on this matter), communication systems were not robust enough and the blast furnace personnel were ultimately unprepared for the loss of cooling water on the morning of 7 November.

144 The failure to inform the furnace team of the proposed switch of transformers meant that they had no opportunity to consider whether to reduce wind. Reduction of wind would, of course, have greatly reduced the risk of the coolers overheating in the event of any reduction in the water supply.

145 When the furnace crew did become aware of the loss of water they reduced the wind – but this took time. Additionally, they were at a position in time where the liquids in the furnace were at a high level – not an ideal time by any means, and not one that would ever have been chosen for process excursions.

146 There were no formal protocols in place for such work – confusion, misinformation or simple misunderstanding was inevitable at some stage.

Blast furnace recovery and abnormal plant conditions

Lesson 9 The specific process of conducting a blast furnace recovery gives rise to additional risks significantly over and above normal operational risks. It is essential that all personnel involved are aware of those risks and there are control measures, including arrangements for effective communication, in place such that adequate risk control is maintained.

147 Post-event it was clear that some personnel involved had little knowledge of precisely what significant risks attended a furnace recovery. Those risks that were foreseen (eg a tuyère breakout) were not adequately communicated to all employees at risk. Control measures even for the foreseen risks were not adequate, for instance, there were a number of unnecessary personnel on the cast house floor after a tuyère breakout risk had been (correctly) identified. Several of these personnel were completely uninformed about the levels of risk to which they were exposed, and need not have been present.

Lesson 10 A specific issue with the recovery of No. 5 Blast Furnace was that as it developed, there was an incomplete knowledge of the changing status of the furnace. During abnormal plant conditions there should be a competent senior manager detailed to retain an 'overview' of the developing situation and to keep a specific watching brief on critical parameters, so as to be able to inform those more intimately involved in dealing with the abnormal situation. Specific parameters in the case of blast furnace recovery operations should include such critical data as liquid iron levels, hydrogen levels and trends.

148 The evidence of the investigation showed that there appeared to be no one with an overall 'watching brief', at a distance from the developing crisis. This manifested itself in a number of ways. For example, even following extensive investigation there remains disagreement as to who knew what, and who was taking decisions on the crucial hydrogen level within the furnace on the afternoon of 8 November. This was an important parameter in the decision-making process, but it remains controversial among those who were there.

149 Another significant parameter was similarly not sufficiently considered in a methodical way – the rising iron levels within the furnace that threatened to endanger the tuyère coolers and produce a water/hot metal event. There was no direct way to measure this, but the skills were present to enable a fairly accurate calculation to have been made and acted upon; this was not done in any effective, structured way. Senior personnel who could have fulfilled this watching brief role were instead 'leading from the front' in attempting to recover the furnace, rather than retaining a more objective view.

Management of change

Lesson 11 A formal system of pre-modification risk assessments should be instituted for any changes (including changes to operating parameters) proposed to safety-related plant and equipment. This should be coupled with post-modification safety reviews. The management of change system should include evaluation and assessment not only by the engineering and operational functions, but also by appropriately experienced and competent safety professionals. Duties and responsibilities for this should be clearly identified. Changes to the physical characteristics of plant should be carefully assessed for any impact on risk profiles and should be carried out with best engineering practice. All such changes should be carefully recorded and subsequently re-evaluated to determine their actual operational impact.

150 There was an absence of systematic evaluation of risk profile changes brought about by the large number of engineering changes undertaken on the furnace over many years. Some of these changes were unimportant and inconsequential, some, ultimately, quite significant in their effect, either individually or cumulatively.

151 Changes were not accompanied by risk re-evaluation to determine their actual operational impact. A prime example was the ad hoc addition of Sorrelor coolers in critical positions on the furnace, with their location poorly recorded and their water supply pipes often taken from the nearest available delivery source – sometimes from the landing below the cooler location. This had a profound effect on the ability of personnel to carry out speedy leak detection.

Decision making

Lesson 12 In emergency situations, there should be management arrangements such that there is a clear 'line of responsibility' for decision making. There should be no doubt whatsoever as to who is making which decisions.

152 Recent changes to working patterns and the introduction of the 'Team Working' protocols within the company had clearly been imperfectly understood by individuals, for whatever reason.

153 The managers and technicians involved during the period of the recovery were very experienced and individually competent furnacemen, but there was considerable doubt in many minds as to what the chain of command actually was, and precisely who was making crucial decisions. In particular, doubt remained as to who was responsible for any decision to take the furnace 'off' and end the recovery process. This may well have led to events leading the decisions, rather than decisions dictating control of events. This is not an acceptable condition in the middle of dealing with high-risk abnormal plant conditions; there should be much greater clarity of responsibility and command in such situations.

Lesson 13 Decisions made by managers under pressure from adverse plant or process conditions present a potential source of significant error. Adequate training and experience is essential, but more precise decision-making protocols should be available for foreseeable circumstances to guide and inform decision making. Careful consideration should be given to providing emergency event-simulation training etc to build operator confidence and skills in emergency or abnormal process conditions.

154 Personnel under pressure, no matter how well trained or competent, are at increased risk of error when making decisions. The managers and senior operators dealing with the furnace recovery were operating in difficult, unusual, process conditions. Adequately precise decision-making protocols were not available to help these individuals – they were largely reliant on experience and 'informed judgment'. The evidence is that this was ultimately insufficient, and it is not surprising that errors were made. The opportunity for building experience in respect of abnormal plant operation is limited on a continuous process plant. Abnormal process conditions are exactly that – not routine or normal, and can be very infrequent. The support engendered by rigorous, carefully evaluated protocols for foreseeable process excursions would be of significant value for personnel in these difficult situations. While not eliminating the need for informed judgments, properly designed protocols would clearly identify where those judgments are needed, and provide the necessary supporting framework.

155 A number of the personnel present had little or no previous experience of dealing with a furnace chill this severe. The watermen in particular were relatively inexperienced in dealing with rapid leak detection in circumstances where methodical work at speed was crucial.

156 Process conditions such as recovery of a furnace, breakouts, power failures, loss of other services etc are by definition relatively infrequent events. The opportunities for training and experience building are therefore few. This is not a situation unique to the steel industry. A method of dealing with this type of challenge is the use of 'table-top' and 'simulation' exercises. These and other techniques, can create intensive experience-building opportunities for all levels of staff, and enable problems to be identified and dealt with in a safe, risk-free environment, where mistakes and errors can be turned into valuable learning aids, not potential disasters.

Design issues

Lesson 14 Opportunities to achieve risk reductions by radical design improvements on blast furnaces are very infrequent. The design of new or extensively rebuilt furnaces should take into account the need to improve the reliability of cooling water supplies and to have suitable pipework layout, valve arrangements and water monitoring systems so as to facilitate prompt leak detection and remedial action.

157 The opportunities for radical improvements in control of safety on blast furnaces are limited by a number of features, not least of which is the infrequency of reline or rebuild. However, there will be opportunities for a rethink of critical items such as instrumentation or basic engineering control improvement – especially with cooling water. One feature of furnace design and operation is clear – cooling water use is continually increasing and is often a determining factor in furnace life. Every window of opportunity should be taken to improve control of this issue.

158 The evidence is that cooling water changes brought about on No. 5 Blast Furnace were assessed and implemented on the basis primarily, if not exclusively, on the ability to achieve more cooling and therefore continued and greater output. There is little evidence to support the view that sufficient use was made of engineering stops to improve, for example, leak detection or redundancy issues.

Lesson 15 The provision of improved monitoring systems, purpose-built for monitoring cooling water parameters on blast furnaces, should be considered. Safety-specific instrumentation of adequate precision should be designed and installed to address specific foreseeable operational and abnormal operating conditions.

159 The post-accident investigation used a considerable amount of recorded electronic data to try to interpret events. This data came from a variety of sources on the furnace: thermocouples, pressure sensors, flow meters, gas analysers etc. None of the equipment had been installed with a primarily safety-related function. It supplied data that was subsequently exploited for safety and incident analysis, but it was not specifically designed for this purpose. There is now available a range of technology which could easily be retrofitted to existing furnaces for the specific monitoring of safety-related parameters both in the normal run of production, and, importantly, for foreseeable abnormal excursions.

160 There should be a detailed review of the need for such instrumentation based upon the foreseeable furnace excursions that are recognised as credible, albeit infrequent, events. The instrumentation should be properly designed and installed with a view to providing operators with information on the precise parameters that foreseeable process abnormalities would generate as risk-critical.

161 The review process should be undertaken by competent furnace operators, safety professionals, and control and instrumentation engineers.

Human factors

Lesson 16 It is essential during abnormal plant or process conditions that all personnel are clear as to who is responsible for decision making and that they have provided adequate lines of communication. Employees should have a precise and clear view of their roles and responsibilities, and be supported by suitable training, procedures and other job aids.

162 There was clearly confusion among several of the employees as to who was actually in charge on the cast house floor. Lines of communication were unclear during the recovery. Several people were at risk who need not have been, had communication of the risk levels been adequate and had they understood the actual condition of the furnace at the time. This was true both for the event as it occurred, and the events that were actually foreseen as credible risks, eg tuyère breakout.

> **Lesson 17** The awareness of the danger of water/metal and water/slag explosions should be raised among all employees engaged in processes where this is a risk. The degree of risk presented by molten materials coming into contact with water continues to be not fully appreciated.

163 The assertion was made by some experienced employees that water on metal was somehow relatively ‘safe’ and that water ‘under’ metal (or slag) was the danger to be avoided. This is not always true: water and molten metal/slag contact of any sort should always be regarded as potentially very hazardous. Generally, water lying undisturbed on top of molten metal or slag will merely boil off to steam. However, there are foreseeable conditions where water on top of molten metal can still be extremely dangerous. This point was made following the Appleby-Frodingham Inquiry in 1975 (British Steel, 1976): ‘It was a known fact that it was extremely hazardous to pour hot metal or slag onto water and it was relatively safe to pour water on to hot metal/slag in situations where little danger of entrapment of the water by hot metal existed. However the incident has highlighted a third situation, namely where water comes into contact with hot metal in a confined space, such as a torpedo ladle, or in any other situations where the possibility of entrapment exists...’.

164 There needs still to be a re-evaluation of the collective experience on this subject. The received wisdom on this matter within the molten metals industries is not necessarily always accurate and can lead to failure to correctly evaluate the risk presented by water and metal contact.

165 HSE has investigated a number of serious molten metal/water explosions that have occurred subsequent to water being initially on the surface of the metal and safely boiling off. Almost any physical disruption of this relatively stable state can lead to catastrophic consequences. This disruption can come from simple movement of the system, breakdown of the water/metal interface, or the inability of the steam generated to have sufficient room to escape. All water/metal interactions should be considered as potentially very hazardous.

166 There is a need for a perception-shift within the industry on this matter, and it should be brought about through the risk assessments and training processes for all jobs and tasks involving molten materials were there is possible water interaction.

> **Lesson 18** The process risks associated with safety-critical plant, especially ageing plant, should be thoroughly understood through rigorous assessment processes, with these being subject to regular review. Specifically, with water systems on blast furnaces, a ‘leakage tolerant’ attitude should not be allowed – especially with older furnaces. Such raised acceptance of water leaks increases the risks of an adverse event occurring at some point.

167 The investigation showed that there was a substantial difference in the occurrence of water leak events, on a routine basis, over a long period of time, between the older No. 5 furnace and its newer neighbour, No. 4 Blast Furnace.

This may have been indicative of a 'leak tolerant' culture developing at No. 5 Blast Furnace because of its history and age. This was potentially a serious development as it invoked a mindset of accepting leaks as inevitable on the older furnace. Water leaks had clearly been identified by senior managers as being the potential determining feature for the final conclusion of the operation of the No. 5 furnace – there is little evidence that this had actually led to better leak prevention and detection on this furnace.

Actions – the company

168 No. 5 Blast Furnace was demolished and rebuilt to a more modern design – one which does not feature a lap joint.

169 There was a substantial Company Panel of Enquiry conducted according to established company procedures. This Panel included management, technical, and trades union representatives. A number of industry-recognised experts were consulted.

170 An Investigation Report and Recommendations were produced by Corus UK Ltd as a result of this process.

171 The main actions following these reports were:

Working procedures

172 In the event of failure to remove liquids from the furnace or to achieve good tap hole blast connection for a maximum of two hours, the furnace will be taken off blast for review.

173 Procedures for dealing with water ingress have been thoroughly reviewed.

174 A chilled hearth situation will now involve taking the furnace off blast for formal risk assessment reviews.

175 Recovery procedures have been amended.

176 A new role of 'panel monitor' has been created. This is a competent individual whose sole function will be to monitor furnace operational parameters at all times.

177 The role of team leader has been modified to now involve two individuals: one on the cast house floor, one in the control room.

Furnace design

178 The new furnace has a closed water cooling system for stack and bosh areas. The provision for leak detection and control is greatly improved.

179 The tap hole-to-tuyères distance has been increased to 3.9 m at the new furnace.

180 A computer program has been developed to aid estimation of liquid levels within the furnace.

181 Top gas analysis has improved. Hydrogen levels can be detected sooner.

182 Overall computer systems for monitoring have been improved.

183 The new control room is situated remotely and provides greatly enhanced operator protection.

184 Blast walls at critical valve manifolds have been improved.

Energy Department

185 A new control standard for voltage monitoring has been put in place, especially at switching operations. Alarm systems have been incorporated.

186 Switching operations will require prior information to be given to the blast furnace operators.

187 Alarms have been fitted to the electric Sulzer pumps to provide 'high current' alarm.

Actions – Health and Safety Executive

188 The nature and matters surrounding the deaths of the three Corus employees in the incident legally required that there be a Coroner's Inquest with a jury. The finding of the 17-day Coroner's Inquest was 'Accidental Death' in each case.

189 Following extensive consultation with the Police and Crown Prosecution Service, and with the benefit of detailed legal advice from HSE's Legal Office, and Counsel, two charges under the Health and Safety at Work etc Act 1974 were laid against Corus UK Ltd.

190 These charges alleged breaches of sections 2(1) and section 3(1) of the Act. (Section 2(1) of the Act relates to company duty to employees, section 3(1) relates to company duties to non-employees, ie contractors and members of the public.)

191 The company was subsequently prosecuted in the Crown Court and pleaded guilty to both charges. Corus UK Ltd was ordered to pay a fine of £1.33 million, with £1.74 million costs also being awarded.

Appendix 1 Photographs

Figure 3 General view of the blast furnaces at Port Talbot. No. 5 furnace (and associated stoves, gas plant etc) is to the left, No. 4 furnace to the right

Figure 4 Rear view of No. 5 Blast Furnace

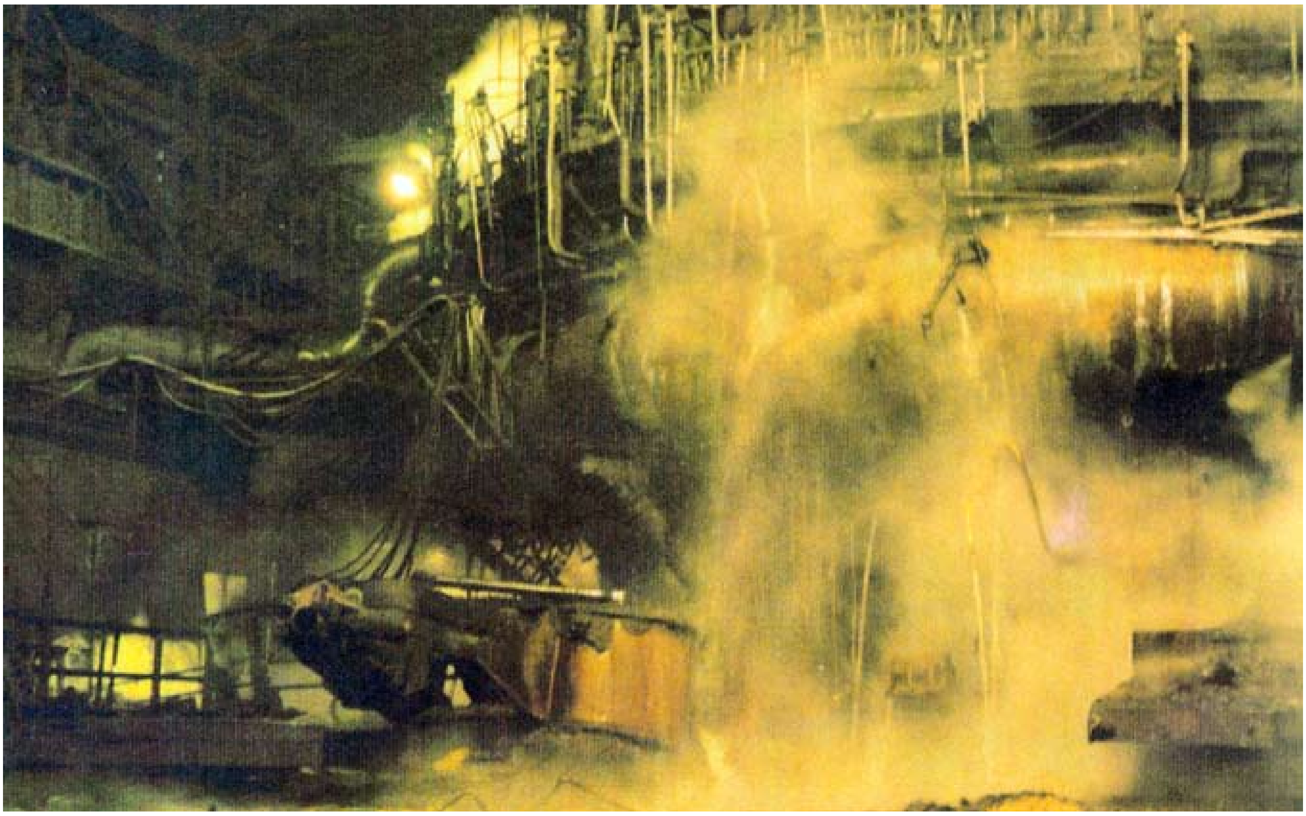


Figure 5 View of cast house floor shortly after the explosion

Pumps

Figure 6 Margam B Power Plant showing furnace water pumps

Figure 7 Furnace steam turbo water pump

Figure 8 View of steam governor

Appendix 2 The cooling system

Coolers

1 As part of HSE's investigation, HSL was asked to carry out tests in an effort to determine the amount of water ingress from the blast furnace cooling system into the furnace prior to the rupture on 8 November 2001.

2 Water pressure tests to locate failed coolers on the furnace stack and on the bosh were carried out in situ during the period over which the furnace was dismantled. The entire stack, bosh, tuyère jacket, lintel stave and Sorrelor cooling systems were pressure tested in situ. The following coolers were found to have leaks:

- two Sorrelor coolers positioned above tuyères 6 and 22;
- six copper flat coolers in the bosh above the north tap hole; and
- tuyère numbers 2, 3, 7, 8, 13, 16, 17 and 20.

3 In addition to in situ testing, water flow-rate tests were carried out at HSL on one bosh cooler bank and three discrete bosh flat coolers at a supplied pressure of 2.5 bar gauge. The water flow rate through each damaged bosh flat cooler was calculated from the amount of water collected from the discharge over a timed period. This would represent the maximum water flow able to enter the furnace from the damaged coolers prior to the incident and was measured as 750 litres per minute (44 m^3/hr). The water flow rate from one bosh cooler, number 34/4, was 520 litres per minute (31 m^3/hr). (Note: One cubic metre of water weighs one metric tonne.)

4 These findings do not necessarily establish the actual extent of water ingress into the furnace prior to the incident. They represent the maximum water flow rates and hence quantities that may have flowed into the furnace. The coolers tested were only those which did not appear to have suffered mechanical damage during the dismantling phase, ie only those coolers where evidence of thermal damage was apparent. It remains possible that some of the thermal damage may have occurred during or after the accident.

5 It should also be noted that several of the Sorrelor coolers had been sealed off prior to the incident on 8 November 2001. As it was not known when those Sorrelor coolers had been sealed off, they were excluded from the water flow-rate tests.

Figure 9 Examples of coolers: a section of dismantled furnace shell (minus the refractory lining). The yellow-sprayed coolers are Sorrelors, the darker lozenge-shaped coolers are plate coolers

Figure 10 Sorrelor cooler showing inlet and outlet connections

Figure 11 Plate cooler showing inlet and outlet connections

Figure 12 Example of burnt-out Sorrelor cooler

Figure 13 Example of burnt-out plate cooler

Figure 14 Dismantled furnace section showing coolers

Appendix 3 Refractories

The refractory lining

1 HSE and HSL assessed the extent of the damage to the furnace refractory resulting from the incident on 8 November 2001. It also considered the campaign history of the furnace, the effect that this would have on the refractory lining and the relevance of this to the incident itself.

2 The HSL investigation involved a complete assessment of the state and extent of the refractory lining as observed during the dismantling process and the examination of core samples of evidence of lining failure and to assess the extent of wear. The investigation reached the following conclusions:

3 Overall the state of the refractory liners in No. 5 Blast Furnace was as could reasonably be expected after a campaign of this length.

4 Refractories in the top cone and off plates were found to be in good condition and had not suffered major damage or cracking as a result of the incident on 8 November 2001.

5 Most elements of the throat armour had been removed in the latter part of the campaign and not as a result of the incident. Mid-campaign repairs to this part of the furnace were found to be increasingly necessary to maintain the original internal circular lining contour which is necessary for optimum operation of the material charging system in use at the plant.

6 The refractory lining in the upper and mid-stack was in good condition with less than 50% protrusion of the cooler plate length exposed. Little or no evidence was seen of the 100 tonnes of silicon carbide gunning material applied into the mid-stack in June–July 2001.

7 Notwithstanding that the 1989 reline (prior to the campaign in question) included the extensive use of high-quality silicon carbide refractory backed by plumbago in the lower stack, the upper parts, specifically cooler rows 6–10, suffered the most severe refractory wear.

8 The bosh design/configuration is somewhat unique to the Corus operation in South Wales. The system had been successfully developed, initially at Llanwern, in the 1970s and was subsequently incorporated into No. 5 Blast Furnace and No. 4 Blast Furnace at Port Talbot. The design is based on closely spaced, high-quality copper internal plate coolers which are welded to the shell in combination with a relatively low-duty aluminous fire clay refractory. The latter has a low thermal conductivity but is less prone to cracking in certain temperature regimes. The density of the cooler spacing is increased so that the working lining contour is maintained further away from the steel shell and there is less chance of breakout. It appears that the system worked well throughout the campaign, but measurements taken during the dismantling process indicate that the lining was becoming extremely thin in critical areas of the bosh above tuyères 17–22 immediately before the incident.

9 Refractory in the lining in the bustle main was in good condition but there had been excessive slag encroachment, particularly in the north, east and west sectors. It is thought that the majority of this slag may have been deposited prior to the incident in November 2001. However, slag of higher fluidity and different colouring and texture was found in the bustle main above tuyères 20–22. It is thought that

the more fluid slag may be more closely associated with the incident on 8 November 2001. Post-incident surveys carried out by Corus and HSE showed that whereas most of the blow pipes were blocked, many of the down legs were still clear or only partially blocked, particularly in the 12–21 tuyères sector.

10 The hearth was in good condition, as were its refractories, in spite of the incident.

Figure 15 Interior of furnace stack prior to refractory removal

Appendix 4 Recovery of a blast furnace

1 A 'chilled hearth' or 'chill' is a loss of thermal activity in the hearth area. It is usually caused by water ingress or burden slip, ie the sudden downward movement of cold materials charged to the top of the furnace such as coke, limestone and iron ore. The consequences of a chilled hearth can possibly require shutting down of the furnace, in addition to increased risk of adverse events such as uncontrolled furnace breakout.

2 The process of bringing a furnace back to its normal operating use following a chill is known as 'recovery'. Recovery is also required if a furnace has been off blast for a period of time.

3 The recovery process may be relatively short and straightforward or a much longer and more complicated process requiring careful management.

4 The objective of a recovery is to regain lost thermal activity in the bosh (eg following water ingress) to 'dry out' water contamination caused by water in the hearth area and to return to full blast delivery.

5 Recovery may involve a number of different measures taken by the operators of the blast furnace, including increasing the level of coke being added to the furnace. This increases the level of combustible materials at the bosh and hence increases the likelihood of further thermal activity. Blast rate can, in addition, be reduced.

6 It is important to tap iron and slag that has already been formed. Failure to do so can lead to rising liquid levels and a breakout – this is the loss of containment of molten material, generally iron, through the furnace structure into the cast house. An uncontrolled breakout is clearly very dangerous. It is especially likely if molten iron levels within the furnace reach the water-cooled tuyère noses.

7 It is vital that liquids that are being produced (iron and slag) are drained away from the tuyères.

8 Lancing is a recognised technique used to tap off liquid slag and iron. It is the use of a thermic lance (a steel tube fed with pure oxygen) which is inserted into the furnace via a tap hole to burn off materials and allow liquids to run off. In addition to attempting to burn a hole into contact with the liquids known to be in the furnace, another purpose of lancing is that it introduces additional combustion and therefore thermal activity into the furnace. The objective of this is that the number of tuyères that are active can increase and a normal 'raceway' effect can be established. (A raceway is an active reaction area in the front of the tuyères.)

Appendix 5 Mechanism of the event

The mechanism of the rupture

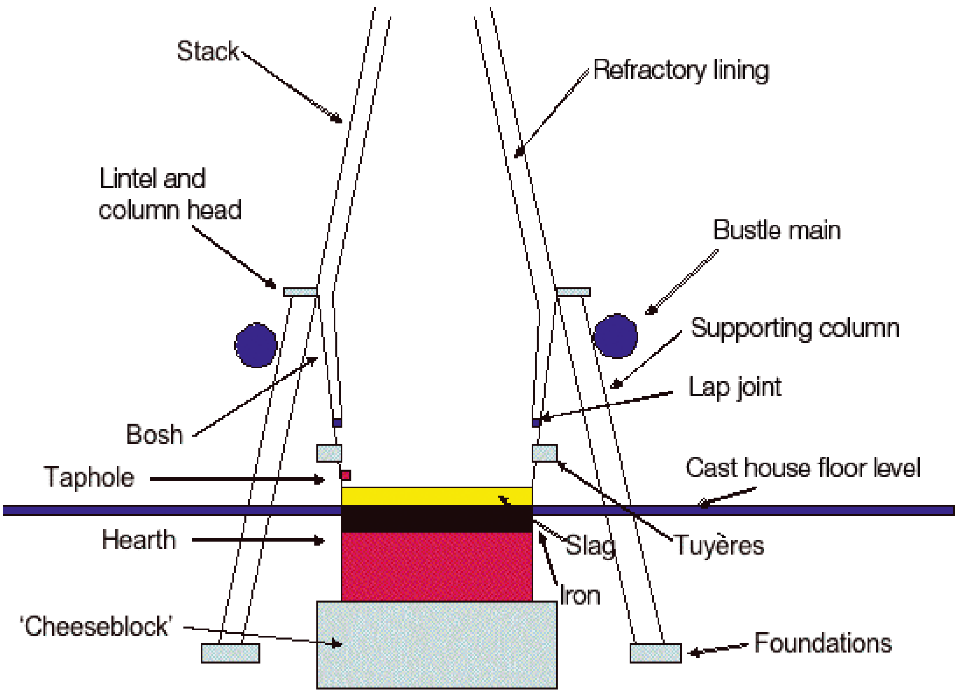
1 A major part of the HSE/HSL investigation focused on the precise mechanism of the rupture at No. 5 Blast Furnace.

2 Five possible theories of failure were considered. They were:

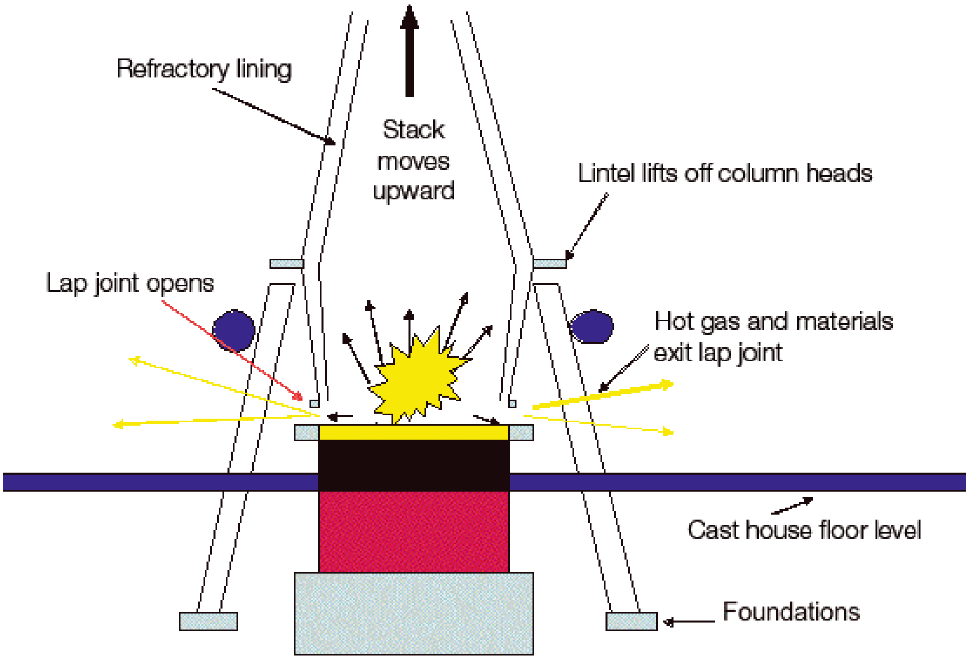
(i) An induced molten metal/water interaction caused an immediate and significant furnace over-pressure leading to its failure by separation at the lap joint causing the bosh, belly and upper stack assembly to be launched vertically to a height approaching 0.75 m.
(ii) A significant vaporisation of water, initiated by radiant exchange between coke burden/slag and displaced water, caused sufficient pressurisation of the furnace to result in (i) above, although perhaps with a much lower, albeit sustained, pressure over a period of about 5–6 seconds.
(iii) Molten iron in the raceway above the chilled hearth and surrounding the active tuyères accumulated and, as its level rose to contact one or more tuyères, these started to burn through, allowing high-pressure water to become intermingled with molten materials sufficiently to cause rapid vapour generation and the further explosive interaction sufficient to separate the furnace.
(iv) An event such as (iii) above caused alternatives (i) or (ii) above.
(v) An event such as described in (iii) above caused a massive burden slip and compression of gas sufficient to cause separation.

3 The significant feature is that all the above models require a water/hot material interaction.

Figure 16 Simple diagrams showing movement of furnace during event



(a) Prior to event



(b) Furnace movement during explosion

4 The precise mechanism of the events within No. 5 Blast Furnace on 8 November 2001 has so far resisted definitive determination despite considerable analysis by a number of experts, both from within the industry and HSE. The precise mechanism and extent of over-pressure remains disputed.

5 The one feature that all investigators have agreed upon is, however, that the explosion was without doubt brought about in some fashion by the interaction of water and hot molten materials in the lower reaches of the furnace.

Appendix 6 Protective clothing

1 Firstly, it should be clearly understood that the protective equipment being used at the time of the accident was primarily designed and manufactured to protect against relatively minor molten metal or slag splashes. It was most certainly not designed or constructed to protect wearers against the type of event which actually occurred on 8 November 2001.

2 All personnel – employees of Corus and contractors – were supplied with and required to wear appropriate personal protective equipment (PPE), in accordance with the requirements of the Personal Protective Equipment at Work Regulations 1992. The equipment is provided to give protection from basic mechanical hazards, environmental hazards (such as noise) and protection from hazards associated with the blast furnace process. The equipment comprised foundry boots, appropriate standard jacket and trousers, protective helmet, visor, gloves and hearing protection.

3 The personnel at work on the furnace stack at the time of the explosion were also wearing self-contained breathing apparatus as a precaution against poisonous blast furnace gas which may be present at higher levels on the furnace. This is a routine precautionary measure above the tuyère belt area. All personnel were equipped with personal electronic gas monitors for the detection of blast furnace gas.

4 As part of the investigation equipment removed from the three deceased and other personnel was inspected and analysed by HSL. The examination confirmed:

- the majority of personnel were wearing the PPE supplied by Corus. A number of items of PPE that should have been worn were not received at HSL. It cannot be said with any certainty whether items missing were not being worn at the time of the incident or were removed at the site by colleagues or emergency personnel offering assistance to the injured; and
- the majority of the clothing appears to have afforded the protection from metal splashes reasonably expected of it. Where sustained contact with hot metal was suspected the outer clothing was breached but in many cases further penetration was halted by under clothing. Only in the most severe cases did penetration occur through underlying clothing.

5 The overall conclusion reached by HSE was that the personal protective equipment performed to, or exceeded, the standards to be reasonably expected of it, and that in many cases where the demands on it exceeded its design criteria, it nonetheless substantially mitigated the injuries actually suffered.

Appendix 7 Lintel bolts

1 Plans and drawings of the plant indicate that there were originally 64 bolts fixing the furnace lintel to its eight supporting columns. This would be by eight bolts on each column.

2 The bolts and columns had been subject to modification before the incident on 8 November 2001. At least four bolts had been removed and there was evidence of weakening of the nut/threaded shank on a further 16 bolts. The evidence suggests that on 8 November 2001, 44 original bolts and 18 bolts of reduced strength were in place at the lintel/columns.

3 All of the bolts between the furnace lintel and seven of the supporting columns had failed. On the eigth column (designated Column 3) the weld between the upright section and the top mounting plate had failed.

4 The failings of the bolts were mechanical in nature. The most common failure mode was brittle fracture. A small number of bolts, most of which were on Column 7, had been subject to ductile failure. Thread stripping failure had occurred in a small number of bolts but only in those with modified nuts (some nuts had apparently been flame cut to increase accessibility during furnace assembly to facilitate construction).

5 There was significant corrosion of the fracture surfaces produced after the bolts and the weld failed.

6 The nut end of column bolts on the exterior of the furnace had been subject to severe corrosion and in a few positions the nuts were not found when the furnace was dismantled.

7 The bolts had been manufactured from a range of steel types. Testing indicated that the bolts would have had significantly higher strength than the minimum required for the relevant grade shown on the furnace engineering drawings.

8 The steels used in the manufacturing of the bolts were susceptible to brittle fracture at ambient temperatures and/or higher rates of loading.

9 The characteristics of the corrosion on the fracture surfaces were similar to corrosion found on original surfaces situated near the fracture sites.

10 Accordingly it was concluded that the fracture surfaces had existed and had been subject to corrosion over a considerable period of time before the incident.

11 The similarity in the corrosion suggests that the bolts and welds had fractured some years before the explosion.

12 The most likely reason for the bolt failures arose from a history of thermally induced shell cracking at the lintel joint area of the furnace. This is a known feature of the lintel furnace design and has been observed on other such furnaces. Despite a number of attempted remedies over a period of years, the thermal cracking of the steel furnace shell at the lintel gave rise to gas leaks, which ignited and further induced thermal distortion into the lintel ring. It is believed that this had created considerable loadings within the lattice structure formed by the lintel and the supporting columns at the column heads. The resolution of these thermal forces may well have eventually manifested itself as broken retaining bolts.

13 It should be noted that the manufacturers of the furnace have no record of having suggested any maintenance and/or inspection regime for the bolts, and none was carried out by the company except at the various rebuilds during the furnace life. Where rebuild engineers had found broken bolts, they had replaced them, in some cases by bolts manufactured on site – hence the variation in the metallurgical composition of the bolts tested.

Appendix 8 Timeline of events

Table 1 No 5 Blast Furnace campaigns

	Blown in	Blown down	Years	’000 Tonnes
New furnace	1959	1962	3.58	2 040
Reline	1963	1967	4.42	2 902
Reline	1968	1972	3.92	2 411
Rebuild	1974	1980	5.83	3 429
Reline	1981	1988	7.58	6 590
Reline	1989	2001 (failure)	12.58	14 696

Simple timeline of events prior to explosion

7/11/01	09.15	Electrical fault at power plant – water pumps to furnace fail
	09.25	Pumps back on – all appears ‘ok’
	09.25 +	Elevated hydrogen levels detected
	10.00	Visual checks for water leaks, unable to locate source
	11.30	Decision to take furnace off wind
	13.00	Furnace charging ceases
	14.30	Furnace off wind
	14.30	Checks to locate water leaks – hydrogen remains high
	17.00	Meeting – tuyères 3 and 4 black, water ingress indicated
	18.30	Shift changeover
	19.00	Leak located, Sorrelor coolers over 4, 5, 6 tuyères
	19.10	Coolers grouted and by-passed. Backdrafting
	20.00	Furnace ‘shut up’ – water systems shut
	23.00	Decision made to bring furnace back on wind
	23.30	Back on wind at low pressure – 0.35 bar. Furnace charging
8/11/01	00.30	Tap hole unplugged, producing gas and flames
	01.30	Lancing begins
	02.30	Contact with iron made, slow flow obtained
	03.35	Small run of iron, interrupted by gas. Lancing continues
	06.00	Use of bigger lances starts
	06.30	Shift changeover
	08.30	Iron run – furnace running on 60–70 000 m^3 per hour
	09.00	Management meeting – prepare for shutdown on 9 November 2001
	10.30	Progress meeting – coke rate raised from 560 to 700 kg
	all day	Lancing continues
	12.51	Watermen checking tuyères – only eight tuyères open
	13.00	Watermen checking tuyères – only eight open; hydrogen high
	15.50	Stock rods stop moving
	16.00	Review meeting – actions to be carried out decided
	17.06	Major increase in hydrogen levels
	17.13	Major explosion event

Appendix 9 Predictive tools

1 It is likely that had established predictive methodologies been employed by the company (during the discussions of the Extension Committee, for example) the risk of adverse events at some point in the extended life of the furnace would have been substantially less. The methods that are relevant are those which seek to determine the likelihood and consequences of component and plant and machinery failures. The principal methods, all with variants and often used in combination, are as follows:

- Fault Tree Analysis (FTA);
- Failure Modes and Effects Analysis (FMEA);
- Hazard and Operability Studies (HAZOPS); and
- Layers of Protection Analysis (LoPA).

Fault Tree Analysis (FTA)

2 This method is suitable for both risk assessment and accident analysis. It is a 'top-down' analysis, where a study is made of all the events that, when in a logical combination, lead to an undesired top event. Fault trees are built using 'gates' as well as events. An 'AND' gate is used where all the events at one level must occur for the event to happen at the next level up. An 'OR' gate is where any one of a number of events must occur for the upper event to occur.

3 FTA was first used in the aerospace industry in the early 1960s. By the mid-1990s it was widely used in transportation and manufacturing, as well as in major hazard industries.

4 There was available expertise within the company to employ this methodology – the method was extensively used in 2000 when Corus UK Ltd prepared its safety report for the COMAH Regulations 1999. It is to be noted that this analysis failed to predict the explosion of No. 5 furnace as it actually occurred.

Failure Modes and Effects Analysis (FMEA)

5 This method involves the step-by-step study of plant/machinery components. For each component, four questions are asked: how can the part fail? what are the consequences of failure? how can the prospective failures be detected? and prevented?

6 The technique was developed in the 1950s by reliability engineers. It has been a standard method in many engineering industries, and widely taught to engineers for many years. Again, the methodology was known to Corus.

Hazard and Operability Studies (HAZOPS)

7 Whereas the starting point for FMEA is a specific machine/plant component, HAZOPS's point of departure is a design intention. The method is used to evaluate deviations from the design intent with guide words and property words, for example:

- LESS (guide) WATER FLOW (property);
- MORE (guide) CURRENT (property);
- AS WELL AS (guide) COMPOSITION (property), eg pollutants/debris in water supply;

then for each deviation, the causes and consequences, and necessary preventive action are determined. A team conducts the study, with all relevant people involved, and is usually chaired by a senior safety manager.

8 The method was developed in the late 1960s by ICI chemical engineers. Its use was promoted by the Flixborough explosion in 1974, and later by major hazards legislation such as the Control of Industrial Major Accident Hazards Regulations 1984 (CIMAH). For many years it has been a standard method in the chemical industry, and widely taught, inter-alia, to safety practitioners before 1990. The method was known to the company – HAZOPS was used in 1999/2000 to evaluate the No. 4 Blast Furnace cooling systems at Port Talbot.

Layers of Protection Analysis (LoPA)

9 Layers of Protection Analysis is an analytical tool for assessing the adequacy of protection layers used to mitigate process risk. LoPA builds upon well-known process hazards analysis techniques, applying semi-quantitative measures to the evaluation of the frequency of potential incidents and the probability of failure of the protective layers.

FTA, FMEA, HAZOPS and LoPA – possible effective uses

10 All the techniques embrace failures associated with both human errors and plant malfunctions. They are actually very simple to understand and use. Success in their use depends most on the expertise of the participants in the engineering technicalities, and also knowledge of human factors. They are resource consuming when used to evaluate complex machinery/plant.

11 Each of the methods would have had particular strengths in predicting the specific events and conditions that actually happened. For example:

- FTA would have demonstrated the logical relationship between predicted adverse events and would have highlighted the interactions between plant failures and human errors. It would, for example, have drawn attention to the importance of effective communications;
- FMEA would have been particularly useful in analysing the turbo pumps' governors and trip devices, and assessing the reliability of auto-starts generally;
- HAZOPS would have forced attention on the causes and consequences of partial system failures, particularly with the key property words of water and electricity. For example, the words, with regard to a transformer, MORE CURRENT, would reasonably have led to an understanding of the consequences of a failure to adjust off-circuit tap changers, and the need for low-voltage alarms; and
- LoPA may have drawn together the lessons learned from use of the above techniques to give some insight into the likelihood of some adverse event occurring to the No. 5 furnace and its systems – especially with reference to the pattern of failures at the Energy Department.

Appendix 10 Relevant legislation

1 There is no specific health and safety legislation regulating the operations at blast furnaces in the UK.

2 The principle safety legislation relating to the steel industry was, over the material time, the Health and Safety at Work etc Act 1974, the Management of Health and Safety at Work Regulations 1992, the Pressure Systems Safety Regulations 2000, and the Provision and Use of Work Equipment Regulations 1998.

Health and Safety at Work etc Act 1974

3 The Health and Safety at Work etc Act 1974 imposes general duties on employers to employees and others, including members of the public, to ensure they are protected from the risks arising from the employer's activities.

4 The Management of Health and Safety at Work Regulations 1992 (now 1999) make explicit the general duties on employers the Health and Safety at Work etc Act 1974. Employers are required, for instance, to carry out risk assessments (under regulation 3) and to make appropriate arrangements for the managing of health and safety (regulation 4).

5 HSE's compliance regimes were underpinned by this generally-applicable legislation.

Pressure Systems Safety Regulations 2000

6 The Pressure Systems Safety Regulations 2000 replaced the Pressure Systems and Transportable Gas Containers Regulations 1989. Both applied to blast furnaces. The Regulations place duties on designers, manufacturers, importers and suppliers in respect of design, construction and the provision of protective devices. They also place duties on users in respect of safe operating limits, periodic examination by competent persons, operating procedures, maintenance and modifications/repairs. British Steel/Corus were/are the only users of blast furnaces in the UK. HSE considered the inspection and maintenance regimes were mature and well established.

Provision and Use of Work Equipment Regulations 1998

7 These regulations place specific duties upon employers in relation to the design, use and maintenance of equipment used at work to control the risks presented by such equipment. Clearly these regulations apply to blast furnaces.

Control of Industrial Major Accident Hazards Regulations 1984 (CIMAH)

8 These Regulations were introduced in the mid-1980s. The Control of Industrial Major Accident Hazards Regulations 1984 were deemed by HSE's Solicitor, at the time, not to apply to blast furnaces.

9 The CIMAH Regulations 1984 were introduced following the European Union's 'Seveso' Directive. The HSE Solicitor in 1985 agreed with British Steel's legal opinion that CIMAH did not apply to blast furnaces. A CIMAH 'safety report'

prepared at that time under the Regulations – if they had applied – would have obliged British Steel to carry out systematic risk assessment and to submit its report to HSE.

10 The CIMAH Regulations were replaced by the Control of Major Accident Hazards Regulations in 1999 (COMAH). Blast furnaces were explicitly included in the revised regulations. Corus UK Ltd submitted their Safety Case to HSE in early 2002.

Control of Major Accident Hazards Regulations 1999 (COMAH)

11 The COMAH Regulations apply to blast furnace operations by virtue of the presence of an ‘extremely flammable and toxic’ substance – blast furnace gas – exceeding 10 tonnes (lower-tier threshold). Regulations 7–14 of COMAH, which require safety reports and both on and off-site emergency planning, also apply where the presence of an extremely flammable substance exceeds 50 tonnes (top-tier threshold). No. 5 Blast Furnace exceeded this top-tier threshold. Blast furnace gas is also categorised as ‘toxic’. The COMAH threshold for toxic substances is 50 and 200 tonnes for lower-tier and top-tier thresholds respectively. Formal notification under COMAH was received by the Competent Authority in February 2000 from Corus that the Port Talbot site held an extremely flammable substance greater than the top-tier threshold.

12 The coming into force of, and application of COMAH to blast furnace operations involved HSE’s Hazardous Installations Directorate for the first time. The Regulations required the production of a safety report by Corus to demonstrate that they had taken all measures necessary to prevent major accidents and to limit the consequences to people and the environment of any that do occur. The safety report was required to be sent to the Competent Authority by 3 February 2002. The safety report would be expected to cover controls for the blast furnace gas, which will extend to most aspects of blast furnace operation including water cooling of the lining and safety management systems.

13 Regulation 19 of COMAH requires the Competent Authority to organise an adequate system of inspection of establishments. The programme is required to include at least one on-site inspection by the Competent Authority every 12 months.

14 Regulation 21 of COMAH requires the Competent Authority to notify the European Commission as soon as practicable of major incidents involving fatalities and other specified criteria.

Appendix 11 Previous HSE involvement

1 There was no evidence from British Steel, or elsewhere, of incidents of the nature of 8 November 2001 arising from blast furnace operations prior to the accident.

2 Between 1986 and the late 1990s there were a number of fatal accidents at the Port Talbot works. For many years, all evidence indicated that the root problems to most accidents and dangerous occurrences centred on British Steel/Corus's difficulties in controlling and managing contractors. It was on this issue that HSE focused its efforts.

3 In respect of the accident statistics observed at the steel plants involving contractors, a robust line on enforcement was taken on this issue, both with respect to the contractors and British Steel/Corus.

4 Operational inspectors were aware of the situation and inspectors' reports showed that they were paying attention to it at their interventions. HSE operational inspectors, as part of their intervention programmes, actively contributed to British Steel/Corus rolling programmes of training supervisors and managers at the integrated works to raise their awareness of their duties. Although contractor's employees were involved in the activities at the Port Talbot blast furnace at the time of the incident, the investigations have not found their presence to have been in any way a contributory factor.

Glossary

armouring (throat armour) metal segments let into the refractory brickwork at the throat of a blast furnace to protect it from damage as the charge is dropped into the furnace.

blast (wind) the current of air supplied by a blower to a furnace through the bustle main and tuyères.

blast furnace gas (top gas) the gas given off at the top of a blast furnace. Collected through a gas cleaning plant and used to heat the hot blast stoves and to fire boilers. It is a very low grade (ie low calorific value) gas.

bleeder the pipe(s) at the top of the furnace through which gas can escape if the bleeders are open.

bleeder valve the valve on top of a bleeder which is normally shut.

blow down the process of taking a blast furnace out of commission (eg at the end of a campaign).

blow pipe a pipe which conveys the blast from a blast furnace tuyère stock to the tuyère.

bosh the part of a blast furnace which tapers outwards from the hearth. The hottest and most reactive area of the furnace requiring the most intensive cooling.

burden the material inside the furnace which is reacted to produce iron. Comprises iron ore, flux and coke.

bustle main the blast main, which encircles the lower part of the blast furnace and from which connections are made to the tuyères.

campaign the period in which a blast furnace is in operation between major relines.

carbon monoxide a colourless, odourless gas produced in iron making. It is highly poisonous even in low concentrations.

cast to release the molten iron from a furnace by tapping it or opening the tap hole.

cast house a building at the front of the blast furnace where the casting of iron is done.

casting the process of tapping a blast furnace.

charging the act of loading materials into a blast furnace.

clay gun (mud gun) a hydraulic cylinder used to force refractory clay into the tap hole to form a plug between casts.

cold blast blast air under pressure which has not yet been passed through the stoves to become ‘hot blast’.

Davy cone a mechanical, conical 'valve' in the gas cleaning plant. Raised and lowered to alter gas flow of the exhaust gases and maintain furnace top pressure.

dead man solid material in the bosh region which reaches down through the raceway from the burden down to molten material in the hearth.

distributor (Paul Wurth top) a mechanical device at the top of a blast furnace to spread the charge evenly in the furnace stack.

downcomer the pipe leading down from the offtake of a blast furnace to bring the gas down to ground level or to the gas cleaning plant.

drilling the start of the tapping operation of a blast furnace. A remotely controlled drill is used to drill into the tap hole clay before an oxygen lance is used to hole through to the molten iron.

dust catcher a closed chamber in the exhaust gas system of a furnace in which the velocity of the gases falls and the heavier dust settles out at the bottom from where it can be removed.

furnace lining (refractory) refractory materials on the inside of the furnace to resist the action of heat and chemical erosion by the contents. There are many forms according to the particular conditions and they are renewable (by gunning or at reline).

gas cleaning passing blast furnace gases through a variety of processes to clean them before use.

grouting (of a cooler) injecting refractory grout into a damaged cooler to seal it and prevent water ingress into the furnace.

gunning mechanical spraying of refractory material in the furnace stack to replace refractory brick lost during the campaign.

hearth 1 The bottom of a blast furnace lining – made from carbon blocks. 2 The bed or working part of a blast furnace which holds the molten metal.

hot blast cold blast after it has been heated by the stoves. Blown into the furnace under pressure through the bustle main and tuyères.

injection (of coal, steam, waste oil) tubes inserted through the tuyères to introduce coal, waste oil or steam into the furnace to improve operation and efficiency.

lancing using an oxygen lance to burn solidified iron (skulls) at the tap hole to allow the molten iron to flow out of the tap hole.

lap joint the overlapping joint in the furnace stack to allow for expansion where the upper stack meets the bosh.

lintel the fabricated steel ring which encircles the stack of a lintel furnace, supported by the columns and supporting the upper stack.

oxygen lance a steel tube 3/4' or 1' diameter through which oxygen is fed and used to burn into the furnace.

plate coolers copper plates containing waterways inserted into the furnace through the shell and refractory brickwork to provide cooling to the furnace.

raceway the area in front of the tuyères which is occupied by hot blast blown into the furnace.

refractory see 'furnace lining'.

scrubber a vertical closed vessel in a furnace exhaust gas system in which the waste gases ascend through sprays of water. Dust is washed out of the gas and collects as a sludge at the bottom of the scrubber.

skip hoist a wheeled container hauled mechanically up rails to the top of the furnace where it automatically inverts to discharge burden into the furnace.

skull the shell of cooled iron and slag which may build up on the lining of a blast furnace.

slag the non-metallic impurities removed from iron ore in a blast furnace and drawn off in molten form.

slag notch the aperture through which slag is tapped from the furnace.

slag pool the area into which molten slag is directed after it has been skimmed off the molten iron. Once cooled it is broken up and removed by machines.

slip (burden) sudden movement of the burden in the furnace after it has been bridged, 'scaffolded' or hung up.

snort valve a valve in the cold blast main of a blast furnace designed to be opened to atmosphere so reducing blast without stopping the blast turbine.

Sorrelor coolers cylindrical copper coolers containing waterways. Introduced into the furnace shell and refractory to provide additional cooling.

stack that part of the blast furnace from the top of the bosh up to the throat armour.

stave cooler large, heavy, hollow iron castings, incorporating steel water pipes built into the refractory to provide cooling.

stoves large, vertical steel cylinders lined with refractory and heated by gas. The cold blast is heated in the stoves before it enters the hot blast main and is blown into the furnace through the bustle main and tuyères.

tap to let iron and slag flow from the furnace by removing the clay plug from the tap hole which holds it in the furnace.

tap hole the hole(s) at the front of the furnace through which molten iron is allowed to flow as required.

tap hole drill a large remotely controlled mechanical drill used to drill the refractory clay plug out of the tap hole to allow iron to flow from the furnace.

throat the narrowest part of a blast furnace at the top of the stack.

torpedo rail-mounted steel vessels which are refractory lined to receive molten iron made in the blast furnace. Towed by locomotive from the blast furnace.

troughs refractory-lined gullies in the cast house floor along which molten iron flows to the grids from where it pours into torpedoes located under the cast house.

tuyère the end of the blast pipe conveying hot blast into the furnace.

uptake a vertical pipe leading up from the top of the blast furnace to meet the downcomer and lead the furnace gases away. Four uptakes are common.

wind (blast) the air supplied to a blast furnace (hot blast).

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