Investigation of an acetylene cylinder explosion incident

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This paper describes the investigation into an incident in which a dissolved acetylene [DA] cylinder exploded during the filling operation at a facility in GB. The investigation was carried out by the Health and Safety Executive (HSE). At the end of the investigation HSE had produced an understanding of the failure mechanism. Acetylene is an unstable explosive gas that is stabilised in the cylinder by dissolving it in acetone within a porous mass. The direct cause of the incident was a combination of an initiation event and the failure of the charcoal porous mass / acetone system to suppress that initiation. Major learnings from the investigation covering the valve design, the potential for human error on safety critical tasks, the management of ageing mobile equipment, and the role of the acetone / porous mass stabilisation system are presented.

It was found that the valve design facilitated a number of failure mechanisms that could result in an initiation event. The short-comings of the methods used for checking the integrity of the charcoal mass are considered, particularly in the context of the ageing cylinder population. The potential errors in the acetylene: acetone ratio resulting from the procedures used to control this are also described. The filling process in operation at the plant at the time of the incident placed a significantly high reliance on human control of safety critical and complex tasks. There was no human error identification and analysis undertaken for these safety critical and complex tasks. This resulted in a very high potential for significant human error. The historical context of the site, the developments close to it and the consequences in terms of local disruption following the incident are also described. Learning points were identified for industry in the areas of human factors and reliance upon human interactions for safety critical tasks, the potential impact of cumulative errors in safety critical tasks and the management of ageing equipment, including mobile assets such as gas cylinders.

Incident Summary

At approximately 14.50hrs on Thursday 7th January 2010, an acetylene cylinder exploded whilst an employee was working on the filling racks at a dissolved acetylene (DA) bottling plant. The plant was built in the 1920s when it was in quite a remote location. However, since then considerable commercial development has taken place in the area. The incident cylinder caused life changing laceration and burn injuries to one employee and two further employees suffered injuries including temporary hearing loss and shock. Fires that developed on the adjacent filling lines from the ignition of acetylene leaks as the cylinder burst were allowed to burn for eight days. Due to the potential for further acetylene cylinders exploding, a significant exclusion zone was set up and maintained by the emergency services for several days. As result, considerable disruption was experienced by local businesses following the explosion and a main train line was also closed at one stage until it could be protected.

The fire service had placed video cameras within the filling plant following failure of the cylinder and these showed the flames that were established within the plant (Figure 1). The total acetylene release rate was calculated from the observed flame lengths. This, together with an estimate of the building ventilation rate, allowed a decision to be made to safely extinguish the flames and allow the acetylene to vent to atmosphere. Each cylinder valve was eventually turned off to isolate the acetylene supply and prevent further venting to atmosphere.

Figure 1. Fires of leaking acetylene following the initial cylinder explosion

The incident affected only the dissolved acetylene filling plant, specifically the area that contained the acetylene compressors and filling racks. At the time of the incident there were in excess of 800 'full' cylinders either connected to the racks or free standing in the area, with a further 600 empty cylinders waiting to be filled. On the site there were, in total, more than 4000 DA cylinders of various sizes and fill levels. Of these, more than 3000 cylinders were known to be full.

The incident cylinder had fractured into three pieces which were projected in different directions (Figures 2 and 3). The largest section included part of the top of the cylinder. As the cylinder burst, this part was projected eight metres along the gangway between the filling racks. The valve stem was retained in the cylinder top and had fractured level with the cylinder top. The middle part of the cylinder was projected towards the adjacent filling rack, hitting and damaging three cylinders before finally coming to a rest two metres from its original position. The bottom part of the cylinder was projected over the filling rack, impacting cylinders in the adjacent rack, coming to rest approximately six metres from its original position.

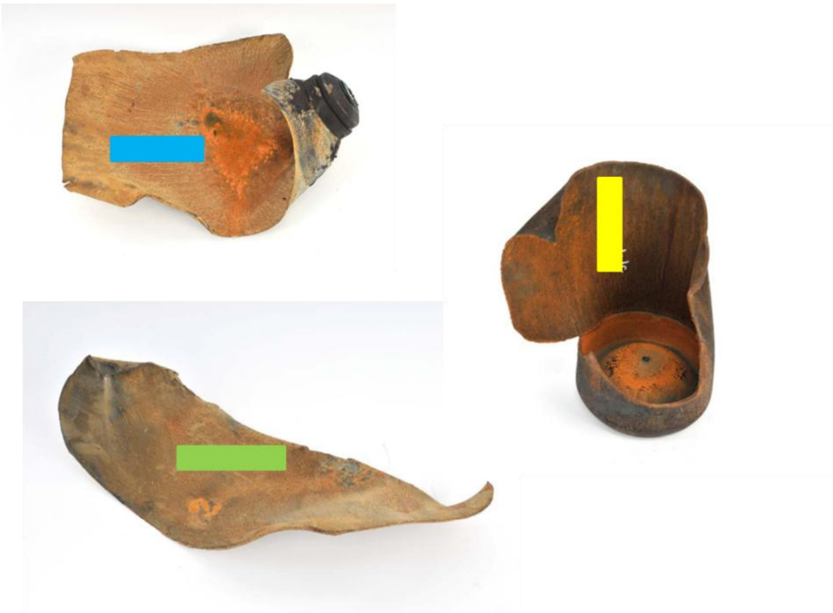

Figure 2. The three fragments of the incident cylinder - colours relate to flight paths shown in Figure 3

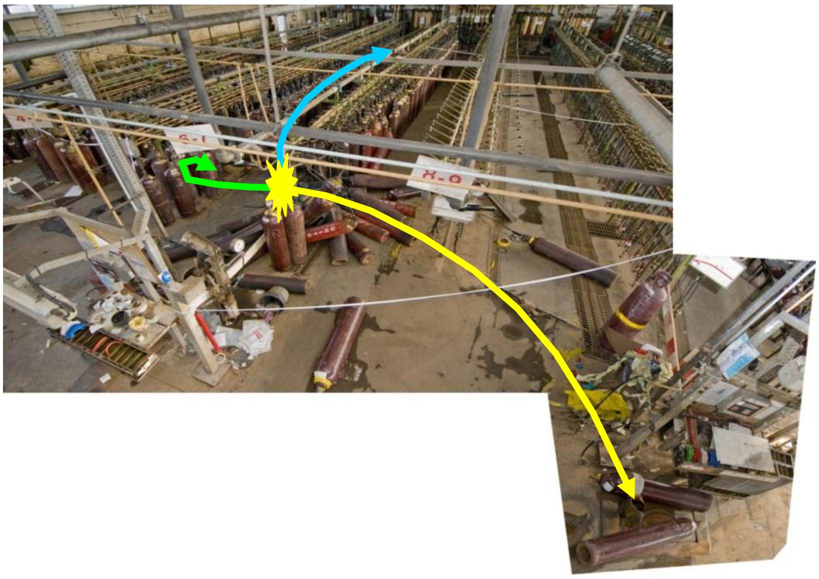

Figure 3. Indicative flight paths of the three parts of the incident cylinder. Blue arrow – cylinder top, Green arrow – cylinder middle, Yellow arrow – cylinder bottom

When the incident cylinder burst, it is believed that the bottom part of it came into violent contact with the adjacent cylinder, forcing this cylinder to the side and upward. The impacted cylinder, attached to the filling hose, swung into a near horizontal position until the tensile force on the hose caused it to rupture. The impacted cylinder was then projected through the air, hitting several other cylinders, before striking a wall 19 metres away.

The filling rack pipework was distorted due to the forces exerted on it by the filling hose as the cylinder burst and also by the skittling of adjacent cylinders. Several small fires on the filling racks were generated during the incident due to acetylene leaking from joints being ignited by the fireball that resulted from the cylinder burst.

The fires, which developed from ignition of acetylene leaks on the adjacent filling lines, were allowed to burn for eight days.

The damage to the DA plant building was minimal, being confined mostly to broken windows. As the building had originally been designed and constructed for maximum ventilation (to avoid a flammable acetylene/air mixture accumulating), pressure build-up within the building as the cylinder burst during the incident was minimised.

The presence of correctly specified, installed and maintained flashback arresters almost certainly prevented propagation of the initiating event in the cylinder to other parts of the filling plant, thereby avoiding more serious escalation of the incident.

A COMAH Reg 18 Prohibition Notice was served on the company on the 30th July 2010 because, in the opinion of the serving HSE Inspector, the safety measures that had been taken were seriously deficient, with particular regard to the significant potential for human error. The notice prohibited the continued operation of the DA cylinder filling plant, until the risks associated with human error had been assessed and further control measures put in place.

Incident Investigation Summary

The investigation was one of the more complex ones that HSE has undertaken in recent years. The investigation took two and half years to complete, and involved 16 inspectors of varied specialist disciplines, including:

- metallurgists;
- forensic scientists;
- process safety specialists;
- human factors specialists;
- mechanical engineers;
- cylinder experts;
- plant ageing experts, and
- explosives specialists.

The investigation resulted in:

- 22 specialist reports;
- 48 witness statements, and
- more than 2000 pieces of evidence.

Over 160 items were seized during the on-site investigation and taken to the HSE’s Science Directorate (HSL) for further examination. As well as the incident cylinder, several other cylinders were obtained for comparative purposes. Pressure chart recorders were also seized to discover the acetylene charging pressure at the time of the incident. The paper charts had to be carefully restored as they were heavily sooted and wet when removed. Several Bourdon tube type pressure gauges that had been fitted to the acetylene charging racks to provide a visual reading of the line pressure were taken for examination and calibration check. Sections of acetylene filling rack and blow down lines were removed for later examination. Swab samples were taken for analysis from the pipe interiors as the sections were removed, although no unexpected compounds were found. Two wall mounted thermometers were taken for calibration checks, as knowledge of the temperature formed a critical part of the acetylene filling process.

Metallurgical Investigations

Failure of the cylinder

The cylinder had fractured into three parts accompanied by significant, large scale, plastic deformation. Measurements showed that the cylinder had a minimum thickness of 4.1 mm, somewhat lower than the specified minimum of 4.76 mm. At an operating pressure of 17 bar, this would have resulted in a hoop stress of 42 MPa. Based on tensile properties, a pressure of 260 bar would have been required to cause cylinder failure. Such pressures are conceivable from a decomposition of acetylene in the cylinder.

Macroscopically, the fracture surfaces exhibited areas of both single sided and double shear. Scanning electron microscopy (SEM) showed that failure had occurred by microvoid coalescence; both observations were consistent with a ductile overload failure mechanism. There was no evidence of progressive modes of failure, such as fatigue or stress corrosion cracking that could have contributed to failure.

Metallography, hardness tests and chemical analysis showed that the material from which the cylinder had been made was consistent with what would have been normal practice at the time of manufacture.

Failure of the valve

The cylinder valve was of a key operated spindle design, with an upward facing port and operated via an outer spindle component coupled to an inner spindle. The valve had been manufactured in 2005 to the British Standard BS EN 849:1997 from a 60/40 copper – zinc alloy, consistent with grade CW721R in BS EN 12165:1998.

The inner spindle was activated by a screw thread and formed a seal against the valve orifice via a cylindrical soft seat component, shown in Figure 4. The soft seat had been manufactured from nylon 6, 6 and retained in position in a recess by the inner spindle skirt. The nylon soft seat component had a diameter of 8.7 mm and a thickness of 3.1 mm.

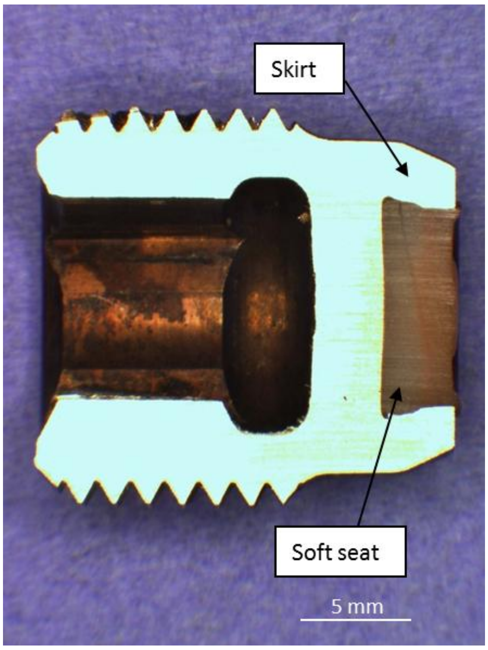

Figure 4. Section through intact inner spindle

The valve was radiographed on receipt; this indicated features consistent with fracture of the inner spindle skirt. The valve was subsequently disassembled and this showed that the inner spindle had fractured around the base of the skirt at a point where the service stresses would have been highest (Figure 5). Fracture had also occurred longitudinally through the skirt, resulting in six individual fragments.

Figure 5. Inner spindle of incident valve

Examination of the fractured inner spindle and the skirt fragments in an SEM showed that many areas of the fracture surfaces were intergranular (Figure 6). The presence of intergranular facets was consistent with an environmentally assisted mode of failure such as stress corrosion cracking (SCC). A detailed survey of each of the fragments showed that there was no evidence of other progressive modes of failure, for example, by fatigue.

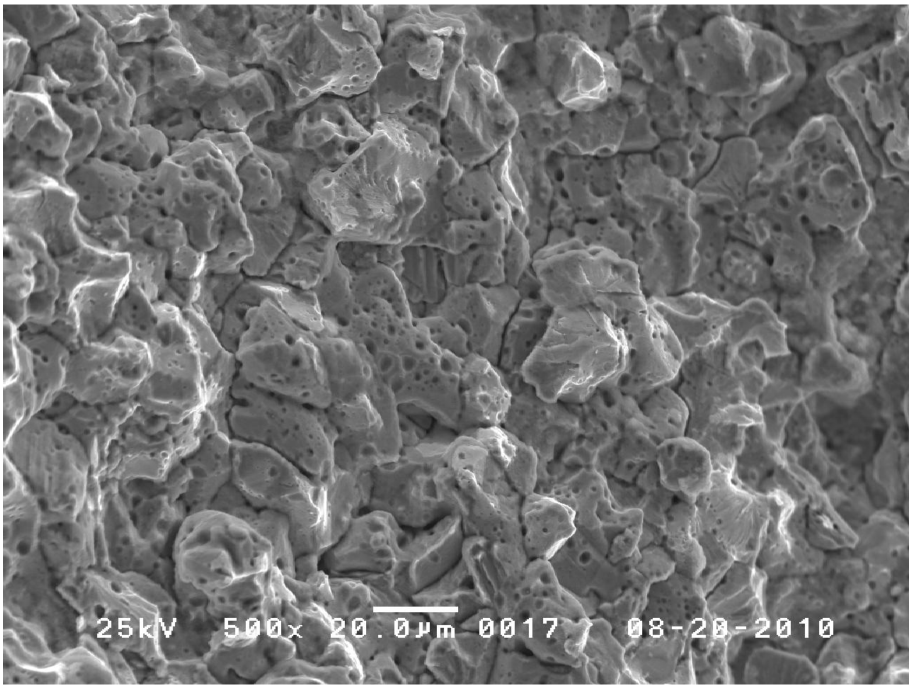

Figure 6. Intergranular surface of inner spindle

A longitudinal section through the inner spindle was mounted and polished to a 1 µm finish and examined optically. This showed that the fracture path was intergranular; secondary intergranular cracking was also apparent close to the fracture surface (Figure 7).

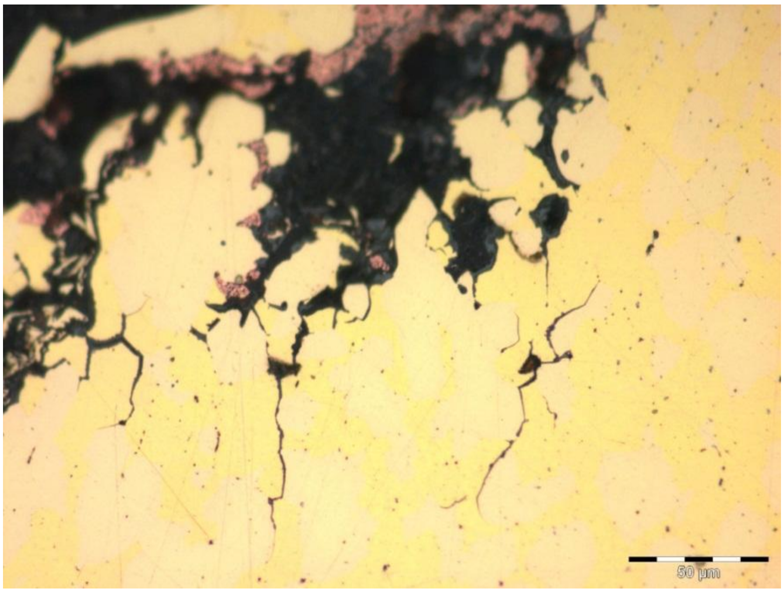

Figure 7. Detail of intergranular cracking and dezincification

A polished section and etched section showed that the microstructure was a fine grained α/β alloy, containing small grey inclusions. Pink deposits were associated with both the fracture surface and the secondary cracking. The deposits appeared to be volumetric and in some cases were associated with a darker grey material.

Examination of the as-polished and etched surfaces in the SEM confirmed the intergranular nature of the cracking. X-ray mapping, using an energy dispersive spectroscopy technique, of the fracture surface and the areas of secondary cracking exhibiting pink deposits, showed that these were associated with a significant reduction in the presence of zinc (Figure 8).

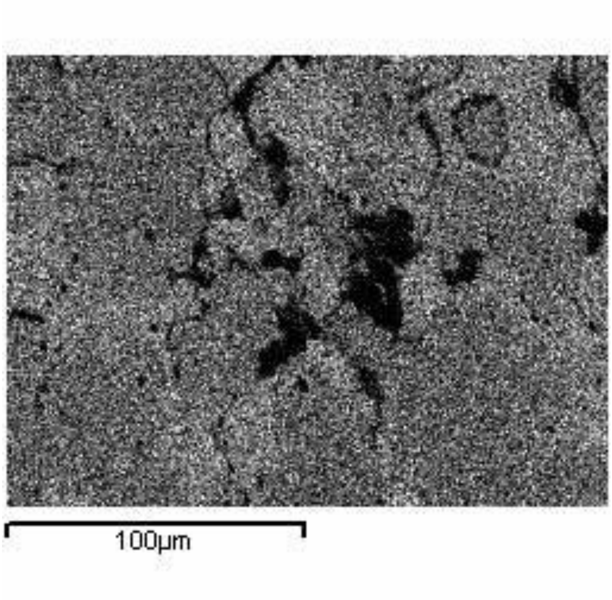

Figure 8. Zinc X-ray map of area of secondary cracking

In summary, failure of the inner spindle was associated with an intergranular crack growth mechanism, consistent with environmentally assisted or stress corrosion cracking (SCC). In addition, areas of metal loss by a corrosion or dealloying (dezincification) process were also observed, in some cases in association with intergranular cracking and in others, remote from it.

Failure of the inner spindle had originated at the change in section in the soft seat recess. Significant tensile stresses are likely to have been generated in this area, resulting from compression of the soft seat during and following valve closure, or as a result of swelling of the soft seat material due to water absorption. It is probable that the stress concentration factor associated with the change in section was sufficient to exceed the threshold for SCC.

Acetylene valves and cylinders are used in a wide range of industries and are potentially exposed to many chemical species. It is not known with any certainty which environmental species led to cracking in this instance; however, ammonia and ammonium containing components are most commonly associated with SCC in copper alloys. A liquid electrolyte is a prerequisite for SCC and water containing dissolved ammonia derived from the atmosphere, often in low concentrations, is known to contribute to SCC.

It is clear that, in the case of the incident valve, dezincification occurred within the soft seat recess of the inner spindle. Furthermore, it is highly likely that both dezincification and SCC occurred as a result of attack by the same active agent, ammonia being the most likely candidate. It is worth noting that acetylene made via the calcium carbide process, as was the case in the incident, is likely to contain some residual ammonia depending upon the effectiveness of the scrubbing system [Miller 1965]. It is also apparent that for attack to occur under the soft seat, the material in this area must have been accessible to the active agent. Capillary action at the interface between the soft seat and the inner spindle skirt by an aqueous environment is most likely.

The valve examined during this investigation had a vertical port opening. In the absence of a valve regulator, this opening could be exposed to the environment. This had the potential to act as a source of active chemical species. Valves with horizontal opening ports would largely avoid this risk factor.

Since the decomposition was reported to have been initiated at the time that valves were being closed, the investigation concluded it was likely that initiation occurred within the valve, ultimately leading to the failure of the cylinder. One possible source of initiation results from a reaction of copper, derived from the dezincification process, with acetylene giving rise to an explosive copper acetylide compound [Brameld 1947; Koehn 1985], via the reaction:

$$C_2H_2 + 2CuCl \rightarrow Cu_2C_2 + 2HCl$$

The potential for this reaction is recognised in BS EN 849:1997 where it is stated that valves for acetylene may be manufactured from copper based alloys if the copper content does not exceed 70 % (by weight). Potential initiation mechanisms including frictional effects and the behaviour of acetylene hydrates are considered below.

Physical factors relating to initiation and propagation of the acetylene decomposition

What initiated the explosive reaction?

Acetylene is a highly unstable gas, with the ability to decompose energetically, once initiated, even in the absence of an oxygen source. There are a number of potential mechanisms for the initiation of decomposition in this incident, all relating to the cylinder valve (which was being closed at the time of the incident). All of the recorded means by which acetylene has been initiated have involved localised heating [Miller 1965]. Experimental work has normally involved electrically induced fusion of a metal wire or a spark; however, any means of generating some sort of hot spot is of interest in the context of an incident involving exploding acetylene. The limiting energy of a short duration heat source necessary to initiate acetylene gas is inversely proportional to the gas pressure [Medard 1989; Kirk 1978]. At the pressure at which the line was operating (17 barg), less than 0.2 mJ of energy is sufficient to initiate a reaction.

There are a variety of mechanisms that can singly, or in combination, give rise to a hot spot capable of initiating a potentially catastrophic explosive reaction in acetylene:

- friction (e.g. in valves);
- shock waves from gas pressure bursting a disc;
- sudden discharge of gas through an orifice such as a bursting disc;
- adiabatic compression of acetylene alone, as an acetylene/air mixture, as an acetylene/oxygen mixture, as an acetylene/nitrogen mixture or the adiabatic compression of other gases such as air, nitrogen or oxygen;
- mechanical shock;
- static discharge;
- pyrophoric impurity; and
- decomposition of copper acetylide.

The potential for each of the above initiation mechanisms was considered as part of the investigation.

As discussed above, the initiation of the acetylene decomposition may well be associated with damage to part of the valve. The damage, associated with copper enrichment due to dezincification, could implicate explosive copper acetylide in the initiation sequence, possibly through mechanical initiation or adiabatic heating. A decomposing flake of copper acetylide as small as 1 µg would be sufficient to initiate acetylene at pressures above 10 bara (~150 psi) [Kirk 1978; Rappoport 2009], as was the case in the incident presented here. However, a number of other mechanisms could not be ruled out.

It is considered unlikely that liquid acetylene would have formed within the cylinder under the conditions believed to exist at the time. Note that solid acetylene hydrate is likely to have formed if, as suspected, water were present in the valve and this may have resulted in adiabatic compression as a result of blockage and then sudden release of pressure into the cylinder.

Potential mechanisms for propagation of the decomposition and failure of the cylinder

Since acetylene is a highly unstable gas, it is supplied to users in the form of DA to improve its stability; the acetylene is dissolved in a suitable solvent, in this case acetone, and the cylinder is filled with a porous mass.

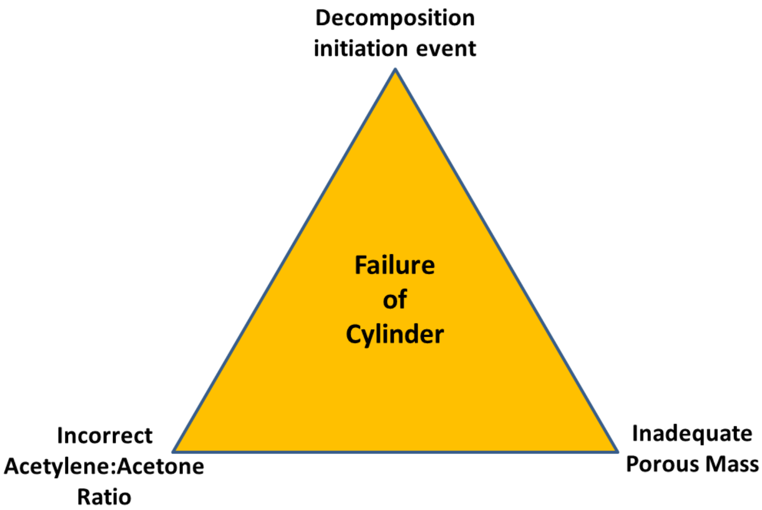

Figure 9. Conditions required for failure of a mechanically sound DA cylinder due to acetylene decomposition

If the stabilisation system comprising the acetone and porous mass system had been effective, an initiation event at the cylinder valve would not have resulted in bursting of the cylinder, providing that the cylinder was mechanically sound. The effectiveness of this system in stabilising the DA depends upon achieving the correct ratio of acetylene and acetone and maintaining an undamaged porous mass (Figure 9).

Acetylene to acetone ratio

Achieving the correct acetylene to acetone ratio is important to avoid acetylene decomposition propagating within the cylinder. It is also important to achieve the correct quantities of acetylene and acetone in order to avoid hydraulically filling the cylinder, with the attendant potential for the cylinder to burst with an increase in temperature. The permissible filling levels for acetylene and solvent for acetylene cylinders can be represented in a "Möller diagram" (AGA). Such a diagram describes the allowable levels of acetone (in this case) and acetylene to which a cylinder may be safely filled. The safe operating region is the area bounded by the "Backfire line" and the "f=0 line". The backfire line represents the boundary for the cylinder to be able to withstand the standard backfire test, in which an attempt is made to induce cylinder failure as a result of decomposition initiated at the top of the cylinder. In a cylinder of acetylene dissolved in acetone, the progress of the decomposition is prevented by the presence of the porous mass and the acetone. In the standard backfire test, a cylinder is filled with the specified volume of acetone and 105% of the target maximum acetylene content. The acetone and acetylene contents are varied in subsequent tests so as to establish the boundary within which the cylinder does not fail. The f65 =0 line represents the boundary for the cylinder to be able to withstand the expansion of the acetylene / acetone mixture on heating a cylinder from 15ºC to 65ºC.

The safe operating region for a D size cylinder is shown in Figure 10. It can be seen that increasing the acetylene to acetone mass ratio would eventually result in exceeding the boundary for failure during a backfire test. It can also be seen that increasing either the acetone mass or acetylene mass above the nominal amounts would eventually result in exceeding the boundary for failure of the elevated temperature test.

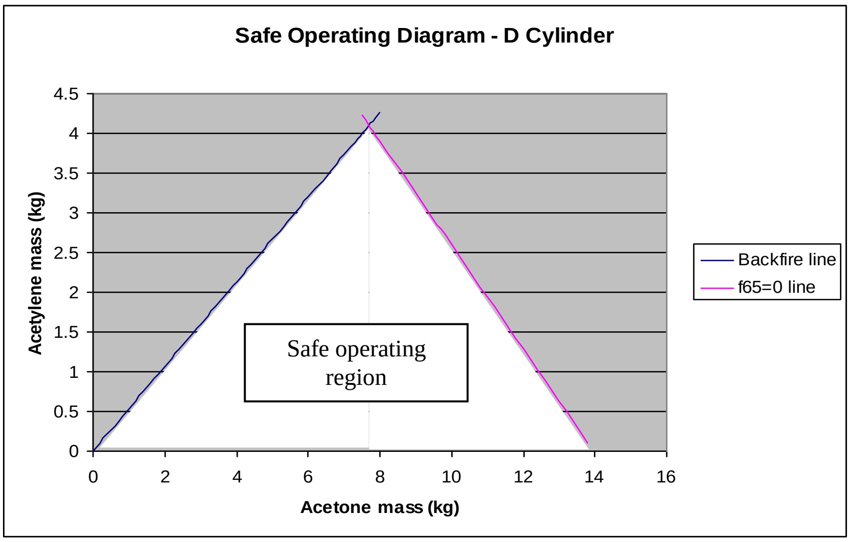

Figure 10. Safe operating area determined for a D size cylinder using the methods given by AGA

Cylinder filling procedure

The filling operation at the time of the incident comprised a number of stages:

- "Gauging" the returned cylinders to determine the levels of gas and acetone in the returned cylinders prior to refilling, as described in BS EN1801:1999.
- Comparing the results of the gauging with limit values to assess if more acetone is required or if there are concerns about the porous mass.
- If necessary, "blowing down" the cylinders to remove residual acetylene prior to further treatment.
- If necessary, adding additional acetone before filling with acetylene.
- Filling the cylinders with acetylene by applying the gas via a manifold that may feed many cylinders (the pressure being measured at the start of the manifold).
- Disconnecting the cylinders and manually re-gauging to assess if they are full enough (or over-filled).

Sources of error in the above sequence include:

- Temperature measurement;
- Rounding errors introduced through conversion charts;
- Errors in the conversion chart for gauging;
- Reliance on manual intervention to stop filling of the individual cylinders.

The temperature used for cylinder gauging was mounted close to the wall of the filling plant, at some distance from the cylinders and therefore, it may not have represented the temperature at the cylinders being filled. Furthermore, the thermometers were found to be in error, with one thermometer having an error of -0.8ºC at an indicated +17.2ºC and -5.2ºC at an indicated -20.0ºC.

The charts and gauges used for determining the quantity of acetylene within the cylinders at start of the filling process were available in steps of 5ºC, which introduced an error in the assessment of the acetylene and hence the acetone levels, as a result of the temperature steps being too large.

It was found that the charts used on the day of the incident had been derived in order to accommodate the unusually cold weather. Unfortunately, they contained a systematic error that introduced further potential deviation in the assessment of the acetylene to acetone ratio.

The above factors may have introduced a significant error in the acetylene to acetone ratio such that it was no longer within the safe operating region where a decomposition would have been contained in the event of an initiation, even if the porous mass was in good condition.

Porous mass

Another important aspect is the management of the porous mass within the DA cylinder. The incident cylinder was 75 years old at the time of the incident and had previously had the porous mass topped up. Cylinders' porous masses were inspected visually, through the open neck, every 5 years and subject to a rodding test. Clearly, this test is only able to investigate the top of the porous mass. Previously, inspections of porous masses were carried out every two years and included a "bump" test, which would reveal the presence of voids beneath the surface. It is of note that, post incident, backfire tests on similar cylinders to the incident cylinder resulted in one out of the six cylinders failing. Prior to the incident there was no evidence that steps had been taken to specifically address ageing issues for charcoal massed acetylene cylinders.

Human factors considerations

At the DA plant a significantly high reliance had been placed on human interaction during safety critical and complex tasks although no human error identification and analysis had been undertaken. The company's internal investigation identified that one of the causes of the accident was a poor assessment of human factors and stated that a human error assessment of safety critical tasks was not undertaken prior to the incident.

The following potential human errors would result in the incorrect ratio of acetylene to acetone, which would in turn result in the presence of free acetylene:

- Errors could occur in reading the gauge, transposing the reading to the cylinder, and marking with the correct colour chalk. Errors at this point would translate into the addition of too much acetone to the cylinder.
- Incorrect gauge plates could be selected if the operator was distracted, or if they read the incorrect temperature. Errors at this point would translate into addition of too much or too little acetone to the cylinder.
- The weighing-on stage involves calculations to determine which cylinders go forward to filling, which go for acetone addition and which get sent for blow down to remove the residual acetylene. As well as the potential for error in the calculation, there was further potential for cylinders to be placed in the wrong pile and sent to the wrong destination, potentially leading to overfill.
- The addition of acetone was reliant upon a correct calculation, a correct physical action (i.e. ensuring that the foot is removed from the pedal on time), and the correct monitoring of the meter (assuming that the meter was working correctly and had been calibrated).
- With 110 cylinders on a rack, each having a chalk mark of its initial acetylene weight, one man is judging how full cylinders are by reading the chalk mark and then sample weighing to check this. Even if the initial acetylene weight is accurate, the risk of missing a cylinder or getting to one too late is considerable. Furthermore the fact that the cylinders are normally filled under a cooling water spray means that the chalk could be partially or completely washed away leading to an obscured or absent marking.
- Other procedural violation issues.
- Other influencing factors such as:
    - a high workload leading to potential for procedural violations;
    - sub-zero temperatures at the time of the incident leading to negative influencing factors on the operators;
    - lack of supervisory deputy on duty at the time of the incident, leading to a lack of control of the operations;
    - a change in normal shift pattern leading to potential for poor handover of safety critical information.

Unfortunately, fire damage to the incident cylinder removed any evidence that an error had definitely been made during its gauging or filling since the only records of these activities were on the cylinder itself (chalk marks / plastic acetone rings).

Over the past 20 years a significant number of new acetylene filling plants built have been more highly automated, reducing the reliance on human operator interfaces.

Lessons learnt

As a result of the investigation it is possible to identify a number of key learning points, some relating directly to the incident and some of wider interest.

Lessons for industry

Design

The investigation highlighted the need for suitable design review processes in equipment for high hazard plant. Following the investigation, a number of changes to valve design have been implemented, including changes to: a) the position of the valve port; b) the geometry of the soft seat recess to reduce the stress concentration factor at the base of the skirt, and c) changes to the material specification to reduce the potential for the development of copper acetylide.

Process control

It is important to fully take into account the effect of assumptions, control measure accuracies and the potential cumulative errors that may result, particularly for safety critical operations. In the case of this incident, the following aspects were identified:

- Unless returned DA cylinders are blown down (i.e. completely emptied of acetylene) before re-filling, significant errors in the acetylene to solvent ratios can be introduced during the gauging process, since the calculation method assumes that the nominal amount of acetone is present.
- Significant errors in acetylene to solvent ratios could occur, particularly where the conversion charts that are used in gauging are available only in temperature steps. Furthermore, it is important to have knowledge of the temperature of the actual cylinder being gauged.
- It is necessary to take into account cumulative errors when considering safety critical activities. In the case of this incident, the gauging and refilling of returned DA cylinders had many sources of potential error, including inaccuracies of equipment used and too wide a temperature step in the gauging charts.

Management of ageing plant

Ageing plant, leading to an increased risk of loss of containment and other failures due to plant and/or equipment deterioration, can also contribute to incidents and accidents. The issue of ageing plant leading to an increased risk of loss of containment and other failures applies equally to mobile assets such as the DA cylinders (including their porous masses). It is not clear whether industry knows:

- the original design life of the acetylene cylinders;
- the characteristics of end of life; and
- how the end of life for cylinders would be determined.

Operators should therefore have adequate arrangements in place in order to effectively manage ageing assets, including mobile ones, such as:

- Ensuring that the company culture accepts that equipment, in this case the cylinders, ages and that all faults are reported and recorded.
- Carrying out a "fitness for service" assessment of each design taking into account the original design and normal usage. From this, a design life can be set, in this case for the cylinders, porous mass and valves.
- Having adequate arrangements in place in order to analyse failure trends so that lessons from failures can be learned and acted upon to prevent reoccurrences. In this case, the failure trends for cylinders and valves would be required.
- Describe the methodology to ensure that the condition of the equipment, in this case the internal condition of each cylinder and the porous mass, are known by the development and use of non-destructive testing. Acetylene cylinders with charcoal masses are currently tested at least once every 5 years (10 years in the case of the more robust monolithic masses). The test includes both external and internal checks, including checks to ensure the integrity of the mass. BS6071 and subsequently BS EN12863 apply. Operators should have adequate inspection arrangements in place in order to detect deterioration of the acetylene cylinder porous mass to ensure it is remedied in good time. This may include:
  - A demonstration that the maximum periodicity of 10 years [ADR P200 'p'] is appropriate;
  - Consideration of deep bump testing;
  - Consideration of radiography inspection techniques;
  - Consideration of the HSE research outlined in RR509 for plant ageing and how it applies to ageing cylinder populations;
  - Consideration of destructive testing of sample cylinder populations based on an ageing assessment.
- Using the results of periodic testing, destructive testing on a representative sample of cylinders, the failure trends for cylinders and valves and the investigations of these failures in periodic assessment reviews.
- Having clear key performance indicators for the assessment process. In this case, record the number of cylinders tested, the number failing the tests, the number rejected, the total top up of the porous mass as a percentage of the total mass in circulation, the number of cylinders withdrawn at time of fill, the number of valve failures and the number of cylinders destructively tested.

It is worth noting that the European transport regulations, "European Agreement concerning the International Carriage of Dangerous Goods by Road," (ADR), do not deal with the specific case of ageing cylinders, though ADR may be followed to control the external condition of each cylinder.

More information on management of ageing assets is given in HSE Research Report, RR509.

Human factors

Human failures are often recognised as contributing to incidents and accidents. Although the contributions to incidents are widely accepted, few operators proactively seek out potential human performance problems. Operators should undertake a Human Error Identification & Analysis [HEIA] or similar for safety critical tasks. In this case, they might include:

- cylinder inspection tasks;
- cylinder receipt tasks, such as pre-filling tasks,
- Cylinder filling
  in order to identify potential human failures that have an impact on major hazards.

Information on identifying human failures is available via the HSE website.

Lessons for the Regulator

Due to the complexities of the investigation discussed here, a number of lessons were learnt by the regulator in particular in relation to management oversight of on-going investigations and management of evidence and material.

Management oversight of on-going investigations

In recent years, HSE has implemented increasingly rigorous systems for the planning and delivery of proactive work. Other initiatives have also sought to improve HSE's delivery of reactive work, including incident investigations. HSE completed a major review of investigations in 2012. This identified a number of areas where improvements could be made to the way in which investigations were carried out. These included investigation timeliness and investigation manager oversight.

In 2014 HSE developed IMPACT [Investigation Management Planning and Capture Tool] a front line operational tool. Its purpose is to provide a framework for planning investigations and recording important management information. It is intended to assist investigation managers and teams to carry out effective and efficient investigations.

IMPACT is principally a planning tool, but its use throughout the life cycle of an investigation will also facilitate the effective management and timely completion of HSE investigations. Furthermore, the completed IMPACT will act as a clear record of HSE's investigation findings.

IMPACT ensures investigation managers:

- Agree an investigation plan; and
- Undertake regular investigation reviews to appropriate timeliness and quality standards and that these reviews are recorded.

Management of evidence and material

The number of specialist inspectors involved and the sheer volume of material being gathered in many HSE investigations are real challenges. In addition, material can be stored or available in multiple locations.

Following this incident and other complex investigations by HSE, it was recognised that a refreshed evidence management tool was required. HSE launched MEMT [Material & Evidence Management Tool] in 2015.

MEMT is a powerful tool, tailored to HSE's needs. All the material that is collected during the investigation is accessible through this platform. It also contains an evidence matrix which ensures that inspectors have adequate details to demonstrate breaches of law that HSE aim to prove. The use of MEMT across HSE ensures a consistent look and a systemised approach to our working.

Investigation Conclusions

The main conclusions of the investigation are summarised:

- A dissolved acetylene cylinder underwent a catastrophic failure, exploding into three parts.
- One employee suffered life changing injuries while two others suffered temporary loss of hearing and shock.
- The explosion and subsequent fire had the potential for multiple fatalities, both on and off site.
- The incident cylinder was 75 years old and was an old charcoal mass type, with a top entry valve.
- There was a combination of free acetylene, a defective porous mass and an initiation source within the incident cylinder.
- The most likely causes of free acetylene were too little acetone and/or too much acetylene.
- The most likely cause of a defective mass was a void which went undetected.
- The potential causes of initiation were friction (due to broken/fractured valve spindles), compression (due to the presence of acetylene hydrates) or a chemical reaction (caused by dezincification leading to the formation of copper acetylide).
- The inspection regime did not take into account the age or history of the cylinder when deciding whether it was fit for re-filling nor confirm compliance with the cylinder's original approval conditions.
- Processes and procedures were heavily reliant on operator intervention with little or no consideration of the safety implications of human errors.

Since the incident the company has:

- Replaced all top entry cylinder valves with new side entry valves;
- Taken out of service charcoal mass cylinders;
- Ceased acetylene operations at the incident site;
- Built a new automated DA bottling plant.

Overall conclusions

HSE's investigation into the acetylene cylinder explosion resulted in a number of learning points, some relating directly to the incident as well as wider learning points for industry. These were in the areas of: human factors and reliance upon human interactions for safety critical tasks, the potential impact of cumulative errors in safety critical tasks and the management of ageing equipment, including mobile assets such as gas cylinders. Consideration of this investigation and other complex incident investigations resulted in improvements to HSE's approach to incident investigation, particularly in planning, management and evidence handling.

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