THE FIRE AND EXPLOSION HAZARDS OF HYDRAULIC ACCUMULATORS

D B Pratt*

The fire and explosion hazards of hydraulic accumulators used in the steel and engineering industries are reviewed. The incident history and possible causes of these incidents are discussed, and comparisons made with off-shore incidents. Proposals for preventing further explosions are presented, along with topics for research.

Keywords: flammable liquids, oil, explosions, hydraulic, pressure vessels, steel manufacture.

INTRODUCTION

Hydraulic accumulators have been used since at least Victorian times to provide a source of regulated hydraulic power. More recently high-pressure systems have been developed for a variety of applications. In the UK, the predominant use has been in the steel industry, for example to control the positioning of the rolls used in rolling mills. They are also widely used off-shore, for example as part of heave compensator systems.

A typical system consists of either a single pressure vessel or a series of vessels manifolded together, with a total capacity of up to 15 cubic metres. The vessel or vessels are part-filled with a hydraulic fluid, the remainder of the space being filled with compressed air at a pressure of up to 350 bar. Some systems have additional vessels containing only air, to act as extra air reservoirs. The air is supplied by a compressor, usually a multi-stage unit, controlled either manually or by pressure sensors in the system. The hydraulic fluid is topped up by one or more high-pressure pumps from a reservoir or mixing tank. An automatic level-control system may be fitted, in the form of a separate narrow column connected to the main vessel at top and bottom, in the manner of a sight-glass. Level probes in the column are used to switch the pumps on and off as necessary. As an additional safeguard, extra-high and extra-low level probes may be provided, and the column and probe arrangement duplicated to allow the probes to be maintained without shutting down the complete accumulator system.

* Health and Safety Executive, Technology and Air Pollution Division, Bootle.

FIRE AND EXPLOSION HAZARDS

To an outsider, the biggest risk in pressure systems such as hydraulic accumulators would appear to be failure of the vessel or the pipework as a result of mechanical defects, for example a latent manufacturing flaw in a component, overpressure through a failure in the operating system, or progressive weakening of a component through corrosion or neglected maintenance. It is factors such as these that in the past have led to extensive legislation on steam boilers and air-receivers in factories and elsewhere. As a result, incidents from catastrophic mechanical failure of pressure vessels are rare, and if they do occur a thorough investigation may well reveal the cause as being one of the above factors.

In the case of systems where there is a substantial energy input, such as air-compressors, there is the additional factor of the heat generated by the equipment. This heat promotes the decomposition and eventual ignition of the oil used to lubricate the equipment. Fires and explosions from this cause are relatively frequent, and in many cases are ascribed to the build-up of coke on internal surfaces. The coke acts as an insulating layer, reducing heat transfer through the vessel wall, and under certain conditions causing hot-spots of glowing carbon. Vaporized oil and carbon monoxide from the burning carbon can then form a flammable mixture. This mixture may ignite, and trigger a succession of explosions downstream. This mechanism is more fully described in BS 6244 (1). Precautions against this type of incident include:-

(1) Choosing of the correct type of lubricant,

(2) minimising the amount of oil consumed,

(3) controlling surface temperatures,

(4) carrying out regular maintenance, and

(5) avoiding, as far as possible, sudden changes in airflow in the system.

Auto-ignition of the oil and ignition by over-heated components are also possibilities. Similar explosions can result from ignition of lubricating oil mist in large diesel engines, where the internal volume of the crank-case is sufficient to allow a violent explosion to occur. There are many examples of such incidents, particularly with marine engines, and at least one case of an explosion in the space under a large forging press.

Ignition of hydrocarbons can also occur in high-pressure systems where high temperatures are not an immediately obvious factor. Examples include two large explosions on US aircraft carriers in the 1950s, involving the hydro-pneumatic systems of aircraft catapults. In these cases, the main factor was considered to be adiabatic heating brought about by sudden release of high pressure air into a dead end.

More recently, explosions have occurred in accumulator systems used on oil rigs to stabilise the drilling platform in heavy seas. In these incidents the pressure cylinders have been ruptured or damaged, pipework split open, and fires started in the vicinity. The hydraulic fluids used recently include fire-resistant phosphate esters, although one incident on a rig in

1978 involved a silicone fluid. In these cases both spontaneous combustion of the oil and frictional heating from high-velocity air flows have been suggested as sources of ignition, there being no other source of sufficient energy apparent.

THE LACKENBY INCIDENT

Land-based accumulator systems have not in the past been considered a significant fire and explosion risk, as they operate at ambient temperature and receive only periodic energy input from a top-up compressor. In 1984 however, an explosion in a steelworks in the North East killed 3 men and devastated the cellar in which the accumulator was situated. The accumulator was a single pressure vessel of about 5.4 cubic metres capacity, containing compressed air and a water/oil hydraulic fluid. Its function was to control roll-balancing equipment in the rolling mill. The normal operating pressure was around 155 bar.

The investigation of this incident was long and complex and involved HSE specialists, BSC staff and external bodies. The fragments of the vessel were recovered and pieced together and by means of a detailed examination of fracture surfaces it was found that initial failure occurred at the toe of a fillet weld at a stool bracket, and was caused by gross over-pressure rather than by inherent weakness. The estimated bursting pressure was 414 bar. Tensile tests and chemical analysis indicated that the steel used was to an adequate standard and examination of the vessel's documentation since installation confirmed that the vessel was in good condition.

The possibility of failure from mechanical over-pressure was considered in some detail but eventually rejected as unlikely, as the pumps and compressors had not been run for some time before the incident and none of the safety devices had operated. There was however some evidence of a chemical explosion, as charring of valve seats was found and there were eye-witness reports of the relief valves lifting in associated pipework. Both of these point to the pressure rise being caused by a fire in the vessel rather than by a sudden gas-air explosion alone.

Four sources of fuel for this fire were investigated:

(a) Hydrogen generated by corrosion or electrolysis,

(b) methane generated by anaerobic digestion of hydrocarbons,

(c) flammable gas introduced into the vessel via the compressor, and

(d) a layer of oil or other flammable liquid floating on the surface of the hydraulic fluid.

The first two sources were discounted after a combination of experiments and analysis indicated that sufficient gas could not be introduced by these routes. The ingestion of sufficient flammable gas was considered unlikely, as a significant quantity would have been required and there was no source of gas in the vicinity. The compressor itself was isolated from the vessel at the time of the incident, and the fluid pumps were not running. This leaves the floating liquid theory. Samples taken subsequently from other accumulators using an oil-in-water hydraulic fluid have shown layers of concentrated oil and water emulsion, and also pure oil, present on the fluid surface. It is suggested that separation of the emulsion may have occurred, the oil floating to the top and being ignited by some means.

The possible sources of ignition of this oil were then considered. The evidence gathered suggested strongly that the source of ignition was internal, as there had been no external energy source, eg the air compressor, applied for some time prior to the incident. The two most likely candidates were electrical equipment and auto-ignition. On the electrical side the only likely possibility was the probes used in level control columns linked to the accumulator vessel. These control systems are of varying types, and a typical unit uses a probe, energised at 12 volts AC, inserted into the side wall of the column. When the probe is in contact with liquid in the column, a current flows through the liquid to the earthed vessel wall. This current is detected, and used to control the liquid pumps and flow-valves. In normal operation, these probes are not a source of ignition, but there is at least a theoretical possibility that ignition can be caused by fault conditions, for example, mains breakthrough to the probe tip. Some work was done on the type of probe involved in the steelworks explosion, using mains voltage, and ignition of an oil layer floating on water at 138 bar was achieved. The resultant fire however was brief, of only 5 seconds' duration, and is not therefore conclusive.

Auto-ignition of mineral oils and hydraulic fluids under pressure has been investigated by several workers and a recent paper by Main (2) summarises and discusses work done in this field. The general conclusions that can be drawn from the data are that auto-ignition temperatures (AITs) tend to drop with increasing pressure, and that the drop can be accentuated by the presence of rust or other contaminants, for example diesel oil. Maximum AITs are however, still high (typically 250° C) compared with the near-ambient temperature in an accumulator. For auto-ignition to occur, local heating must therefore happen. The mechanism which would cause this is not clear; it is suggested that movement of the fluid in normal working may cause a thin film of oil to be deposited on the upper parts of the accumulator, particularly if separation of the oil from the emulsion has occurred. Over a period of time, which may be months or even years, continuous exposure of such a film to high-pressure air may cause oxidation of the oil, possibly catalysed by rust on the vessel sides. Once coke starts to form it would tend to act as an insulating layer and allow heat to build up, causing further oxidation, more heating and so on, until the exotherm accelerates to the point where ignition of the floating oil can occur, and burning can be sustained. This was considered to be the most likely source of ignition in the steelworks explosion.

FIRE-RESISTANT HYDRAULIC FLUIDS

The type of fluid used in the accumulator which exploded was one of a class generally considered to be fire-resistant when properly constituted. The 4 main types of fire-resistant oils are as follows:-

(1) Type HFA, oil-in-water emulsions. These usually contain up to about 5% mineral or synthetic oil.

(2) Type HFB, water-in-oil emulsions. The water content in these fluids is typically 40%.

(3) Type HFC, water-glycol fluids. These are solutions rather than emulsions, the water content varying between 35 and 55%.

(4) Type HFD fluids. These are synthetic materials containing no water, for example, phosphate esters.

The fire-resistance of the fluids containing water depends on the water remaining in the emulsion or solution. Any phase separation of the HFA or HFB types, for example, would reduce the fire-resistant properties of the fluid towards that of the pure mineral oil. The synthetic fluids do not suffer from this problem, but they have disadvantages in respect of cost, toxicity and compatibility with other parts of the system.

The suitability of a particular fluid for an individual application also varies considerably. Most accumulators used in factories use oil-in-water emulsions, the oil acting principally as a lubricant and anti-rust agent. It may also be a factor in seal life, as one firm experienced serious problems with seal failures during trials using water as the sole constituent of the hydraulic fluid. The fire-resistance of oil-in-water emulsions is high, but careful management of the system is necessary to ensure that the emulsion is being maintained, and that the oil concentration is correct. There is a tendency for the levels of fluid in accumulator systems to be maintained by rather ad hoc methods, with additions of oil and water being made without adequate checking of the concentration. This practice may lead to deterioration in the quality of the fluid, and possible separation of the emulsion. The use of synthetic oils rather than mineral oils is preferred, as synthetics can be more readily dispersed as a solution in water rather than as an emulsion.

Accumulator systems used off-shore have recently used fluids containing 100% synthetic oils, reliance being placed on the molecular structure of the fluid to prevent oxidation. Experience has shown that at high pressures these fluids are not completely stable, and the use of nitrogen instead of air is being considered, to minimise contact of oxygen with the fuel source. Solutions of glycol and water are also being considered, as a result of test work on commercially-available fluids.

SOURCES OF IGNITION

Hydraulic accumulators do not normally experience significant heating, the mass of metal and fluid acting as a heat sink. Compressors used to top up the air pressure can introduce air at elevated temperatures, and there is also the possibility of carry-over of carbon particles, as discussed above. In a properly maintained system however, the compressor should be needed to run fairly infrequently, and for most of the time it would be isolated from the accumulator. Also, the incidents that have occurred tend not to coincide with periods when a compressor is in use.

The internal sources of ignition, as described above for the steelworks explosion, are therefore more likely to be the prime candidates for accumulators in general. Concerning the level probes, further work would be necessary to provide conclusive evidence that such probes could be a source of ignition for oil in an accumulator. Indeed, replacement of such probe systems by other external means of gauging may introduce new hazards, and careful consideration of any such proposal would be necessary.

Concerning spontaneous combustion, this mechanism is by no means certain, and further research work would be required to assess its validity or to suggest credible alternatives. In the meantime, however, steps need to be taken to minimise the chance of more incidents occurring, as their potential for causing fatal injuries to persons and large scale damage to equipment cannot now be in doubt.

PRECAUTIONS

The following list of precautions has been drawn up by HSE in consultation with the steel-making industry and with oil suppliers. A suitable format for publicising these precautions is currently being considered.

Mechanical Over-pressure

To guard against failure from mechanical over-pressure, the system needs to be properly designed, installed, operated and maintained. The following points should have particular attention.

(1) The vessel should be designed and constructed to a suitable recognised pressure vessel code, and the pipework, valves and associated equipment designed to an appropriate British Standard or equivalent.

(2) A gas pressure relief valve should be fitted directly to the accumulator. This valve should be sized and set so as to ensure that the safe working pressure of the vessel cannot be exceeded at the maximum rates of gas and liquid inflow.

(3) The pumps which charge the system should be fitted with a liquid pressure relief valve, set to ensure the liquid pressure does not exceed the safe working pressure of the vessel. Stop valves should not be fitted in line with these relief valves.

(4) The accumulator should be examined by a competent person, for example an insurance company surveyor, at least once every 14 months, and certified as safe for use to a specified maximum pressure. In the case of welded vessels, the likelihood of cracking around nozzle plates and at seams of support brackets should be considered. If necessary appropriate non-destructive testing should be carried out.

Fire and Explosion Risks

The following precautions are recommended to minimise fire and explosion risks:

(1) The gas space in the accumulator can be inerted by the use of nitrogen or other inert gas. This may not be reasonably practicable for large vessels, and its use is inadvisable when the equipment is installed in a confined space, for example, a cellar. In these cases, a leak of inert gas may create a risk of asphyxiation. Inerting can, however, be an effective means of dealing with the fire risk and its use should always be considered.

(2) The hydraulic fluid used should be of a type with minimum fire risk. Ideally, a fluid consisting entirely of water should be used, although in practice additives may be necessary to control such matters as corrosion, bacteria and leakage past seals. Where the use of oil is necessary it should be in the form of an oil-in-water emulsion or solution of not more than 5% oil concentration. A synthetic oil capable of forming a solution with water is preferred to a mineral oil emulsion, as the latter is more prone to separation and the formation of a floating oil layer in contact with air in the accumulator.

(3) Whichever type of oil is used, it should be obtained from a reputable supplier, who should be consulted for advice on the choice of oil and its method of use. The supplier should also be asked for his recommendations on the manner and frequency of testing for concentration, hardness and contamination with bacteria or other agents. The correct method of mixing the oil and water should be prescribed and followed, and the use of a pre-mix tank with metered addition of oil and water is recommended. The concentration of the fluid should be regularly checked by measurement, and an automatic level monitoring system, incorporating high and low level alarms, should be provided.

(4) If oil is used in the hydraulic fluid, then unless the system is inerted the accumulator should be drained and inspected periodically to ensure that oil residues do not build up on internal surfaces. Any deposits found will be evidence that free oil is present, and is liable to degradation and possible self-heating. The selection, use and maintenance of the hydraulic fluid may need to be reviewed. Other possible routes for oil ingress, such as compressors and pumps, should be examined.

(5) Any oil found should be removed by, for example, high pressure water jets or steam. The size and shape of the plant may make thorough inspection difficult, even with the use of mirrors, fibre optiscopes and similar equipment. In such cases, the cleaning operation should be done as a routine operation, and to the greatest extent possible. The frequency of inspection will depend on the ease of internal access, and the amount of residues found. An initial frequency of 6 months rising to a maximum of 14 months is recommended.

(6) Oil may enter the system from routes other than from the hydraulic fluid. Carry-over from compressors is one source of oil, and filters and other devices designed to intercept oil vapour in the gas flow should be properly maintained and regularly cleaned. Pumps using lubricating oil should also be checked to ensure oil cannot enter the liquid being pumped.

(7) No means likely to ignite flammable vapour should be present in the system. Any electrical equipment installed in a position where it can come into contact with the gas in the system should therefore be protected against causing ignition. The equipment should be to Zone 2 standards, as defined in BS 5345 Part 1 (3). Guidance on the selection of such equipment is available in an HSE booklet (4).

FUTURE WORK

The above precautions are designed to reduce to a minimum the chances of further incidents occurring, by adopting the basic principles of good design, operation and maintenance. Only inerting is a significant departure from normal prudent operating procedures, and is the only one which virtually guarantees elimination of fires and explosions. It is however expensive, requires careful control to be effective, and in confined spaces introduces a risk of asphyxiation which may well be unacceptable. There still remains a need to identify more precisely the mechanism by which these incidents occur, and to refine the advice to be given to industry. HSE's research laboratories at Buxton are currently designing a research project aimed at doing this. The programme is not yet defined in detail, but is likely to include studies of the degradation of hydraulic oils at high pressures, under conditions similar to those in hydraulic accumulators. In addition an informal discussion group has been proposed, to bring together representatives from industry, HSE and universities to review current developments and suggest further work which may be appropriate.

Of necessity this type of work will be a medium to long-term programme, but the need for industry to implement the basic precautions described above is more pressing.

REFERENCES

1. British Standard 6244: 1982, Code of Practice for Stationary Air Compressors, British Standards Institution.

2. Main, B G, Explosion Hazards in Off-shore Motion Compensators, Proc. Instn, Mech. Engrs., Vol. 199.

3. British Standard 5345 Part 1: 1976, Code of Practice for the Selection, Installation and Maintenance of Electrical Apparatus for Use in Potentially Explosive Atmospheres.

4. HSE Booklet No HS(G)22: Electrical Apparatus for Use in Potentially Explosive Atmospheres, HMSO.