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PREVENTION OF CRANKCASE EXPLOSIONS IN RECIPROCATING COMPRESSORS

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Abstract: Three ignitions occurred in quick succession in the crankcase of a large, reciprocating, hydrocarbon gas compressor. Protective systems limited the effects and led to safe system shutdown. An investigation team found the ignition source to be an electrical discharge and resultant arcing, between the piston rod oil scraper rings and their housing. The insulating properties of the pad fitted between the non-drive end bearing and earth were found to deteriorate with time. A simple monitoring system was fitted to indicate the duration of the pad's effective life.

Experimental work found that the double tangential rings used for low-pressure sealing were ineffective at pressures less than 0.5 bar, although they sealed well at higher pressures. These rings could be energised by the application of nitrogen buffer gas. In evaluating a proposal to replace these rings with side-loaded pressure rings to API 618, it was found that certain manufacturing quality and housing design features could reduce their sealing effectiveness to less than that of the original type. A manufacturing quality plan agreed with the manufacturer has overcome these problems.

Modifications incorporating these findings have been applied to the compressor, and to three others, without any recurrence of the problem.

Key Words: API SLPR; arcing; hydrocarbon gas; ignition; LP seals; nitrogen buffer gas; surface finish.

1. INTRODUCTION:

Four identical reciprocating gas compressors are utilised in a similar, natural gas duty. The machines have six, two-stage cylinders and are electrically-driven, consuming almost 10 MW. Three ignitions occurred in quick succession in the crankcase of one of these machines. The immediate extent of damage was similar in all three events; crankcase pressure relief valves had burst, emission of smoke and a minor emission of noise. Protective systems, including fire and gas detection and module UV detectors, limited the effects to the immediate surroundings of the machine and led to its safe shutdown. No personnel were injured and no equipment was damaged.

An investigation team studied the machine component parts, ancillary equipment, and three sister machines, to discover both the source of the ignition and the reasons for the presence of an explosive mixture in the crankcase. Ultimately, a research project that studied the performance of a range of low-pressure axial sealing rings was instituted. The total duration of the investigation was more than two years.

The original layout of sealing and venting components of the four compressors is shown in Figure 1.

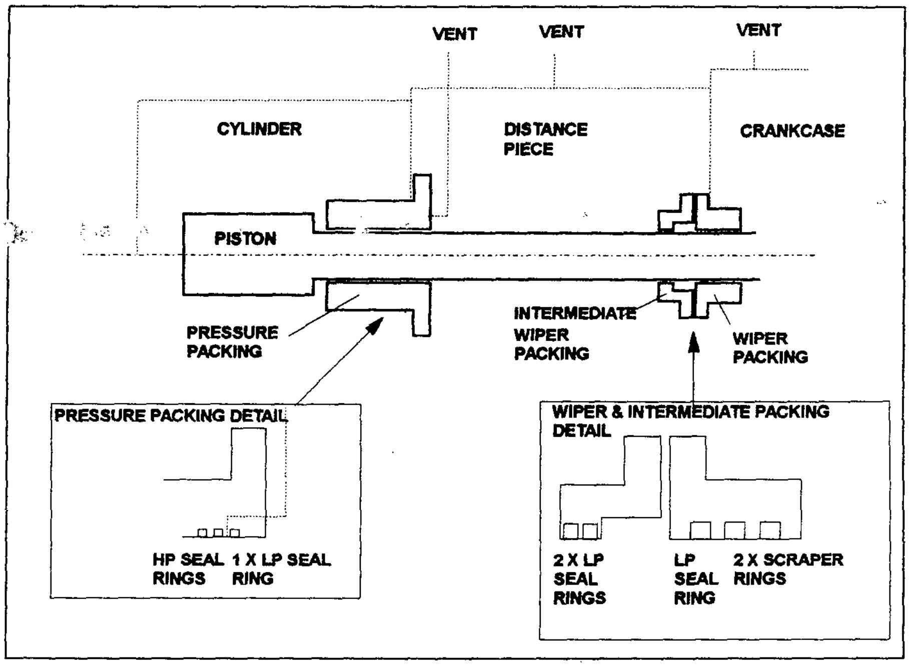


Figure 1. Arrangement of sealing components

2. MACHINE COMPONENT STUDIES:

In the initial, post incident study, the compressor was systematically dismantled in order to ascertain both the causes of gas ingress to the crankcase and the ignition source. No abnormal markings were found on any main or connecting-rod big-end bearings, crosshead pin, slipper bearings or piston rods. No defect was found in the drive motor or other electrical systems. All pressure packings were dismantled and examined in detail. Their appearance was normal. The piston rings and rider bands from all cylinders were also of normal appearance.

Examination of the elements from the piston rod wiper packings found unusual markings on those taken from one cylinder but not on the others. Damage observed on the mating faces of the oil scraper rings is shown in Figure 2. No damage was seen on the faces adjacent to the containers, nor on the containers themselves. Metallographic examination of a cold-mounted section of a typical damaged wiper element showed shallow areas of microstructural transformation typical of the localised pitting that results from electrical discharge. Such transformation indicated that the local temperature had been raised to at least 240°C. A micrograph of this area is shown in Figure 3. Confirmation that this microstructure was typical of electrical arcing was obtained by comparison with laboratory-induced arcing on an undamaged ring.

Identical damage was later identified on wiper packing elements of two sister reciprocating compressors.

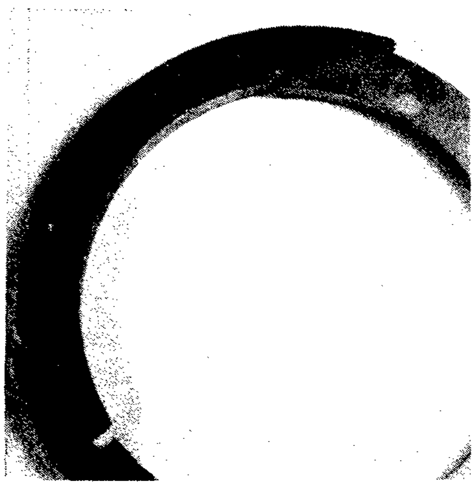
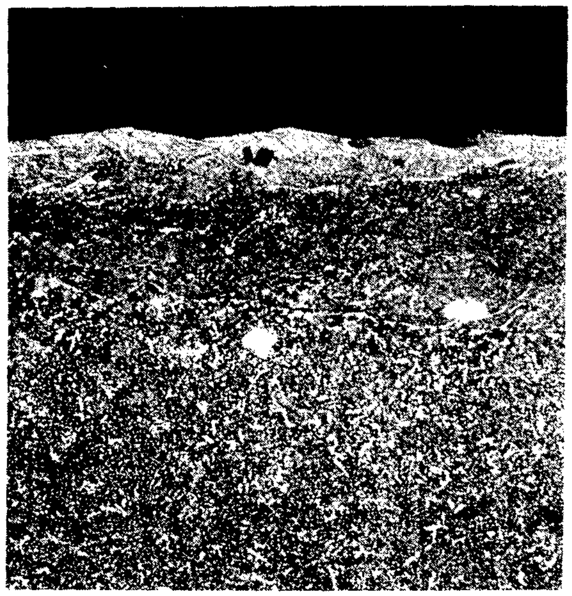


Figure 2. Appearance of damaged rings



200 µm

Figure 3. Microstructure of a damaged area.

3. POSSIBLE IGNITION SOURCES:

Five possible sources of ignition were considered during the investigation. No other sources are considered to be possible. No evidence was found for: a hot-spot within the rotating or reciprocating components of the compressor; discharge of static electricity generated by the passage of oil through the filters; discharge of static electricity generated by oil shear between piston rods and wiper packings; and pyrophoric ignition. They are mentioned here solely for completeness.

3.1. An electrical defect within the machine.

Examination at the time of the incident found that the insulating pad beneath the non-drive end bearing of the drive motor may have been bridged, due to the attachment of protective guards and bearing temperature measurement probes. All potential conductors were removed immediately from all four machines. Further monitoring after this time showed that arcing damage continued to occur. It was determined to examine the insulating properties of the pad beneath the non-drive end bearing.

A simple technique was evolved using a volt meter to indicate the potential difference between the bearing pedestal and frame of the machine. From an initial value of about 300 mV for a new pad with fully reinstated and cleaned metal components, a steady deterioration was found to occur until values as low as 10 mV were recorded. A strong relationship was found between the severity of wiper packing arcing damage and low measured voltages. Investigation showed the two main contributory causes of this deterioration to be shorting of the insulation by gradual leakage of carbon and dirt-impregnated lubricating oil, and filling of the insulated bolt/dowel holes by salt from seawater deluges or washdown.

Changing the insulation type was found to be ineffective in overcoming the problem. The solution was provided by a combination of factors:

- varnishing and proper installation of insulation
- sealing of dowel/bolt holes with silicone mastic during installation
- attention to housekeeping in the pedestal vicinity, for example oil spills, etc.
- cleaning of insulating pad when measured voltage fell below 150 mV.

3.2. Mechanism of arcing

The following theory is advanced in explanation of all of these observations. During normal operation the crankshaft is supported by a hydrodynamic film of oil at the main bearings. This film may be considered to be fully insulating. The drive motor has an insulated non-drive-end bearing, the drive-end radial and axial loads being carried within the compressor. Thus the motor rotor and crankshaft are isolated from the frame of the machine in all respects other than the connecting rods.

Under ideal conditions contact between the big-end bearing and its journal is also inhibited by a hydrodynamic oil film. However, previous work carried out these machines suggested that oil film thickness might be marginal at the TDC and BDC positions. It is known that a high voltage can pass across a bearing oil film when very limited asperity contact is achieved.

Stresses at the cross-head bearing normally exceed those at the big-end bearing, loads being similar but the projected area being considerably less. Thus a low oil-film thickness at the big-end is likely to be duplicated at the cross-head bearing. Electrical contact would then be possible between the crankshaft and piston rod at bottom-dead-centre and to a lesser extent at top-dead-centre also. The cross-head slippers are relatively lightly-loaded and flooded with lubricant at crankcase temperature. A good oil film may be assumed between them and their guides at all times.

At the two dead-centres the piston rod travel reverses, rings in the wiper and pressure packing shuttling from one side of their containers to the other. Work carried out in compressor research at Thornton has shown a very strong surface tension or 'stiction' effect to exist between lubricated rings and container walls. Shuttling of wiper rings may therefore not be instantaneous, but will occur after a short delay determined, for each ring, by the relative proportions of surface tension in opposition to frictional drag from the piston rod. The face of the ring that is nearest to the crankshaft (inboard) in each set is smooth, the others in the set being grooved for oil scraping and having a smaller contact area and, therefore, surface tension force. Thus there is a tendency for the further outboard ring in each set to shuttle a short time before the inboard one. At this instant the inboard ring is in close contact with the container but the rod, flooded with oil, is moving under it. However the outboard ring is in close contact with the rod under the influence of the garter spring. Electrical potentials between the rings change from both at earth to one at earth, one at rod, then revert to both at earth for the remainder of the stroke. Any current flow from the rod to earth undergoes a rapid 'break and make' at the ring interfaces, causing sparking, high temperatures and metal transfer.

4. EXPLOSIVITY OF CRANKCASE ATMOSPHERE

The investigation considered three possible causes of an explosion in a crankcase, given an ignition source. No evidence was found for either oil cracking, due to high temperature or shear rates, or oil mist ignition, but they are included here for completeness.

4.1. Gas ingress

The presence of gas in the crankcase was known from routine flash-point measurements which had shown gradual deterioration over time since commissioning. This was considered to be the most likely cause of the ignitions.

The proportions of liquid and vapour phases in the crankcase were calculated at various levels of gas contamination. It was found that for mixtures of the hydrocarbon gas in service and the crankcase lubricant, the vapour phase and input gas had a straight line relationship. Very small amounts by weight of the gas entering the crankcase dissolved in the oil, the remainder occupying the void or leaving by the vent. At the minimum allowable flash point, 0.020%w of methane, equivalent to 336 litres of gas at NTP, would be contained in the full sump capacity of 1200 litres. In view of the possible flow rate of gas into the crankcase, it must be assumed that the space above the lubricant contained a rich mixture of gas and air. Severe reductions in the flash temperature of the crankcase oil are an indication of high levels of gas. However, this work showed that measurement of oil flash point gives only minimal guidance to the explosivity of the vapour in the crankcase.

These results were used to establish safe operating standards on input of explosimeter test results of the crankcase vapour, which was commenced immediately.

4.3.1. Gas transport mechanisms

The source of gas within the distance piece and crankcase was considered to be inefficiency of the low-pressure (LP) axial seals. All four LP seals fitted in the locations shown in Figure 1 were of the type shown in Figure 4(a).

The double tangential seal is designed to operate with a small axial clearance, which allows the ring to reciprocate slightly with rod motion. The volume displaced by a ring on each stroke equals the product of the ring's cross sectional area and the axial clearance, 1244 mm^3. Provided that a differential pressure exists across the seal, gas will pass it solely due to the effects of reciprocating motion. Leakage of gas to the crankcase by this mechanism could total 134 litres/hour when all six cylinders are taken into consideration.

Small pressures, typically between .15 and .4 bar.g., had been recorded in both the pressure packing and distance piece vent lines, due to backpressure resulting from long piping runs. The resulting pressure gradient between pressure packing and crankcase enabled a significant flow of gas into the crankcase, where it mixed with air already present. This is the explanation for the presence of an explosive mixture in the crankcase.

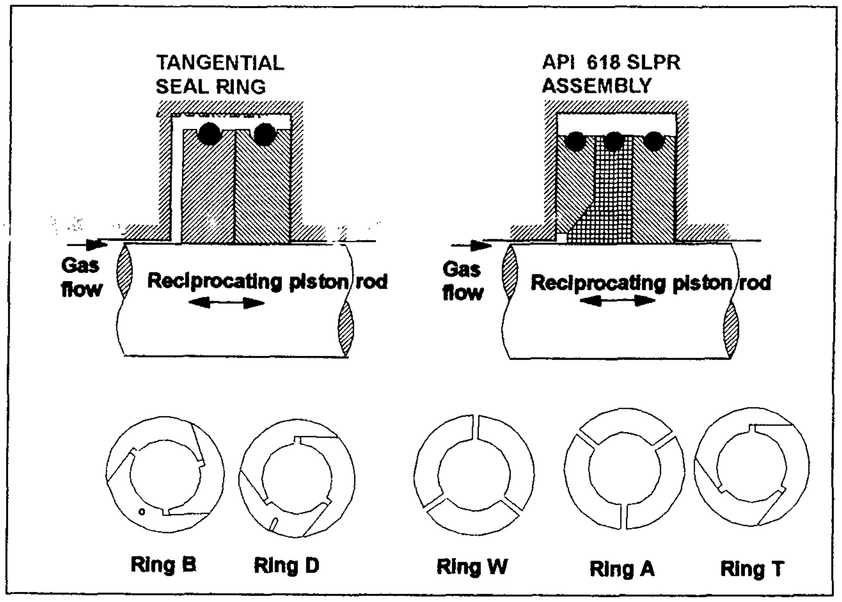


Figure 4. Low-pressure axial seal types, (a) double tangential, (b) SLPR

5. MEASURES TAKEN TO PREVENT FURTHER IGNITIONS.

5.1. Sealing ring modifications

A test rig was constructed for the purpose of measuring typical leakage of gases. The rig, shown in Figure 5, comprised two seal containers mounted back-to-back, with a gas entry port between them. Leakage past the seals was directed to passages equipped with Rotameter flow measurement meters. Elastomeric seals fitted outboard of the containers provided leak-free sealing and were replaced after each test. The piston rod used for this work was of 50 mm diameter and its stroke rate was 300 per minute, identical with that of the compressors.

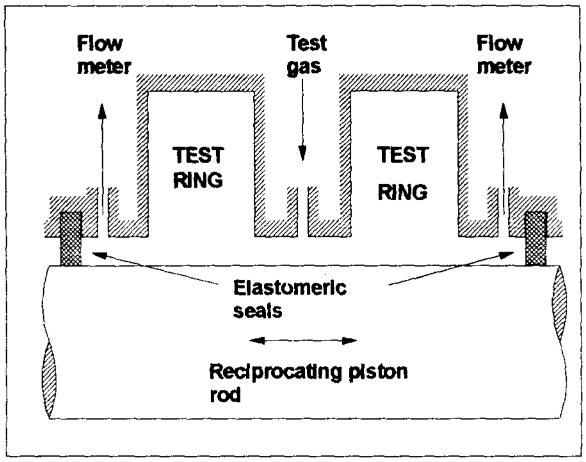


Figure 5. Low pressure seal test rig arrangement

Initial testing was concentrated on the evaluation of commercial quality, LP seals. The early findings were that sealing performance was very dependent upon the quality of manufacture. As shown in Figure 6, whereas some rings sealed with reasonable efficiency others, of apparently equivalent manufactured quality, performed poorly. Immediate improvements to the surface finish of all rings were agreed with the manufacturer.

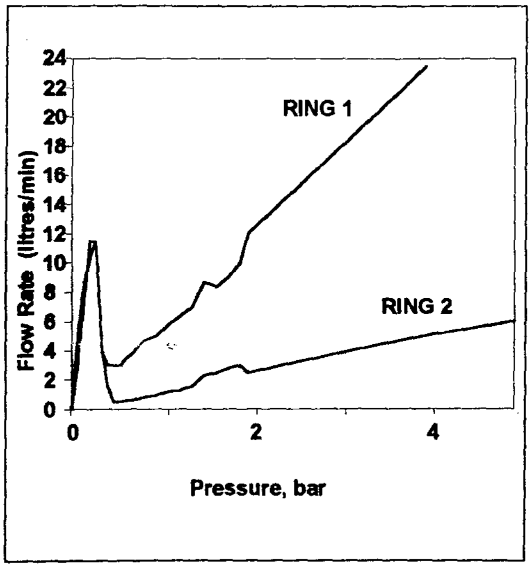


Fig. 6 Leakage of leaded bronze tangential sealing rings to vent

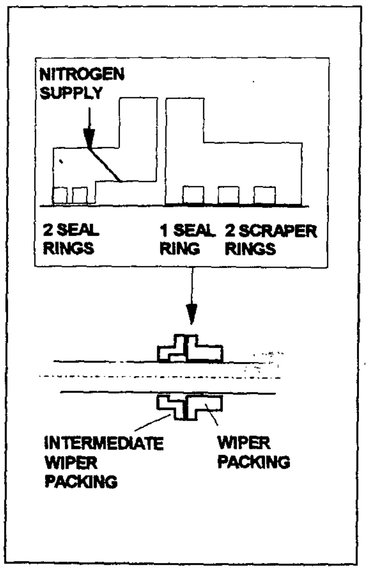


Fig. 7 Nitrogen buffer arrangement

Also shown in Figure 6 is an important finding of this phase of the work. The performance of all seals was poor at the range 0 to 0.5 bar, i.e. the very range within which it would be called upon to operate in practice. This is believed to be a function of friction between the seal and rod, which allows the seal to shuttle from one side of the container to the other, effectively "pumping" gas downstream. As an interim measure it was proposed to inject nitrogen into the space between the intermediate packing and the gas seal of the wiper packing at a pressure of 1 bar. A sketch of the arrangement is shown in Figure 7. No provision was made for nitrogen gas to exit the void, unlike a typical purge. The primary intention of this modification was to energise the seals and to overcome the frictional drag effects of the rod, a buffer of increased pressure being a secondary advantage. A nitrogen blanket, or any high capacity inert system, was not possible in the application for logistic reasons.

Operating experience with this modification has been extremely good. The application of nitrogen gas has resulted in significant savings in used-oil discards, due to reductions in the rate of flash point depression, and explosimeter readings have become either very low or zero.

The test rig was next used to evaluate API 618 SLPR type seals, with a view to replacing the LP seals. The first rings tested were made to the finish standards of those in service in other applications, but these were found to have leakage rates considerably exceeding those of the later LP seals. Examination of these rings after testing showed the main cause to be coarseness of the turned finish of the 45 degree face. The least grooving that remained after machining led to friction between rings, inhibiting the even and constant conversion of radial spring tension to axial thrust. Discussions were held with the manufacturer to define the best repeatable commercial finish that could be provided on sealing surfaces. Agreement was reached that the chamfer faces would be fine-turned to a very high standard and that all radial seal faces would be lapped to 6-12 micro-inch CLA. A second set made to this standard was evaluated, giving the improved results shown in Figure 8.

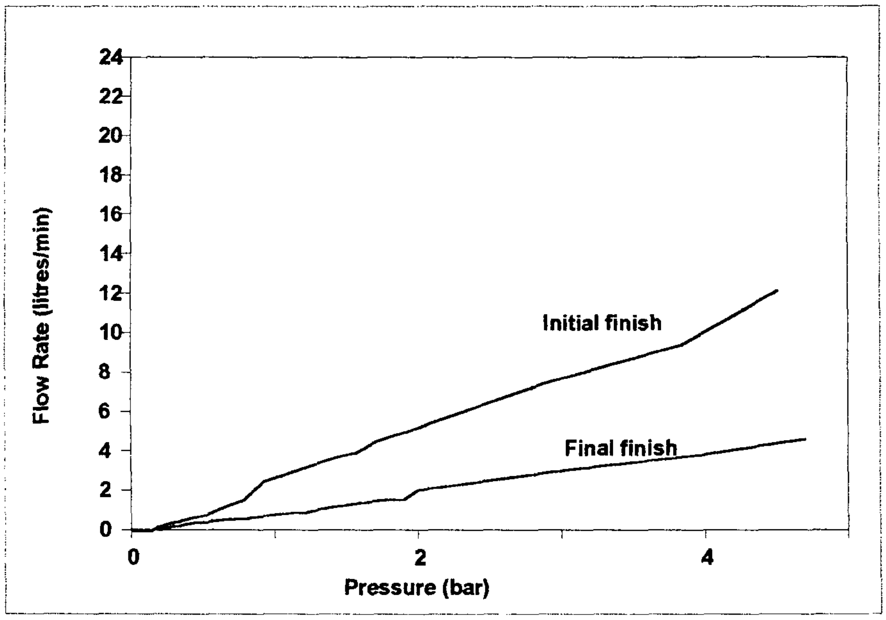


Figure 8. Leakage of leaded bronze SLPR rings to vent.

CONCLUSIONS

Investigation into the crankcase ignitions found that an explosive mixture of gas and air was ignited by electrical arcing. The presence of gas in the crankcase resulted from a deficiency in the design of the tangentially-cut piston rod seals, which were incapable of sealing efficiently. The effectiveness of this type of seal was improved by energising the rings with a nitrogen buffer of 1 bar pressure. Improved seals, of the type specified in API 618, were found to be ineffective until their surface finish had been improved to the highest practicable standards.

Ignition of the explosive mixture occurred when electrical arcing occurred at the rod wiper packings. The driving current was provided by recirculating eddy currents which were caused by a gradual reduction in the properties of the insulating pad at the non-drive end of the electric drive motor. Voltages involved were of the order of 0.3 mV.

Acknowledgement

The author wishes to thank Peter Collins for the design and construction of the rig used in these studies, and Chris Clements for his work in carrying out the seal leakage research described in this paper